DEVELOPMENT AND MANAGEMENT OF HIGH-FIDELITY TEST TECHNOLOGY FOR COMPREHENSIVE PERFORMANCE EVALUATION OF ELECTRONIC WARFARE SYSTEMS IN MULTI-THREAT ENVIRONMENTS

BY

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VOLUME 2 OF 2

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RTO AGARDograph 300
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AG-300-V28

Electronic Warfare Test and Evaluation

(Essai et évaluation en matière de guerre électronique)

This AGARDograph has been sponsored by the Systems Concepts and Integration Panel.

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by
Mr. Martin Welch
Mr. Mike Pywell

The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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AGARDograph Series 160 & 300

Soon after its founding in 1952, the Advisory Group for Aerospace Research and Development (AGARD) recognized the need for a comprehensive publication on Flight Test Techniques and the associated instrumentation. Under the direction of the Flight Test Panel (later the Flight Vehicle Integration Panel, or FVP) a Flight Test Manual was published in the years 1954 to 1956. This original manual was prepared as four volumes: 1. Performance, 2. Stability and Control, 3. Instrumentation Catalog, and 4. Instrumentation Systems.

As a result of the advances in the field of flight test instrumentation, the Flight Test Instrumentation Group was formed in 1968 to update Volumes 3 and 4 of the Flight Test Manual by publication of the Flight Test Instrumentation Series, AGARDograph 160. In its published volumes AGARDograph 160 has covered recent developments in flight test instrumentation.

In 1978, it was decided that further specialist monographs should be published covering aspects of Volumes 1 and 2 of the original Flight Test Manual, including the flight testing of aircraft systems. In March 1981, the Flight Test Techniques Group (FTTG) was established to carry out this task and to continue the task of producing volumes in the Flight Test Instrumentation Series. The monographs of this new series (with the exception of AG237 which was separately numbered) are being published as individually numbered volumes in AGARDograph 300. In 1993, the Flight Test Techniques Group was transformed into the Flight Test Editorial Committee (FTEC), thereby better reflecting its actual status within AGARD. Fortunately, the work on volumes could continue without being affected by this change.

An Annex at the end of each volume in both the AGARDograph 160 and AGARDograph 300 series lists the volumes that have been published in the Flight Test Instrumentation Series (AG 160) and the Flight Test Techniques Series (AG 300) plus the volumes that were in preparation at that time.

Electronic Warfare Test and Evaluation

(RTO-AG-300-V28)

Executive Summary

Control and exploitation of the electromagnetic spectrum has become as much a part of modern warfare as air superiority or dominance of the sea lanes. Electronic Warfare (EW) is the mission area responsible for establishing and maintaining a favourable position in the electromagnetic domain. Test and evaluation (T&E) of those devices used on modern military aircraft to prosecute this critical mission area requires the use of a wide range of test techniques and analytical methods to assure users of the readiness of EW systems to meet the challenges of the combat environment. Actual in-flight testing comprises a relatively small portion of the EW T&E process. As a result, the reader will find that the concentration in this handbook is far broader than 'flight test' – ranging from laboratory efforts to establish the system performance baseline through complex ground-based simulations and finally the limited verification accomplished in the open air range environment.

This handbook is intended as an introductory text dedicated to EW systems T&E. While other volumes in the Flight Test Techniques Series have provided limited coverage of EW system testing, they have been generally aimed at a broad view of T&E and have not resulted in a singular focused handbook on EW test techniques.

While the primary goal of this handbook is to introduce the novice to a disciplined approach to EW testing, it will also serve more experienced testers and programme managers as a concise reference for the EW test process and test resources. It begins with an overview of the test process in the context of the roles and missions expected of EW systems. Subsequent chapters provide examples of test requirements for major categories of EW systems. The final chapters focus on descriptions of specific types of test resources and how they can be linked to simulate predicted operational conditions. A catalogue of some useful EW Test Facilities is included in an annex to this handbook.

The original version of the handbook has been updated to include additional details with previous treatments while introducing new material and greatly expanding the use of figures as an aid to understanding. New material includes discussions about the T&E of infrared countermeasures systems, radio frequency towed decoy systems, low observable systems, and directed energy weapons (High-Power Microwave [HPM] and High-Energy Lasers [HEL]). The chapters addressing T&E resources, modelling and simulation, and lessons learned have been updated to account for advances in the last decade. The annex providing a sample of the member Nations' EW T&E facilities has also been updated.

Essai et évaluation en matière de guerre électronique

(RTO-AG-300-V28)

Synthèse

Le contrôle et l'exploitation du spectre électromagnétique sont devenus une composante à part entière de la guerre moderne, au même titre que la supériorité aérienne ou la maîtrise des couloirs maritimes. La guerre électronique (GE) constitue le champ de mission responsable de l'établissement et du maintien d'une position favorable dans le domaine de l'électromagnétique. L'essai et l'évaluation (E&E) des appareils utilisés à bord des avions militaires modernes pour mettre en œuvre ce champ de mission critique nécessitent une large batterie de techniques d'essai et de méthodes d'analyse, ce afin de garantir aux utilisateurs un niveau de préparation des systèmes de GE qui répondent aux défis de l'environnement de combat. Les essais en vol réel ne représentent qu'une part relativement faible du procédé d'E&E de GE. En conséquence, comme pourra le constater le lecteur, les sujets de ce manuel s'étendent au-delà de « l'essai en vol », allant des activités en laboratoire visant à établir la référence de performance du système jusqu'à la vérification limitée obtenue dans un environnement aérien ouvert en passant par des simulations au sol complexes.

Ce manuel fait office d'introduction aux E&E des systèmes de GE. Tandis que d'autres volumes de la série des Techniques d'essais en vol ont apporté des informations limitées sur les essais des systèmes de GE, ils étaient généralement destinés à fournir un large aperçu des E&E et n'ont pas abouti à l'élaboration d'un manuel unique axé sur les techniques d'essai de GE.

Bien que ce manuel ait pour principal objectif de présenter au novice une approche disciplinée des essais de GE, il est également utile aux contrôleurs des essais et directeurs de programme en tant qu'objet concis de référence pour le procédé d'essai de GE et les ressources d'essai. Il s'ouvre sur une présentation d'ensemble du procédé d'essai dans le contexte des rôles et missions escomptés des systèmes de GE. Les chapitres qui suivent offrent des exemples d'impératifs d'essais pour les grandes catégories de systèmes de GE. Les derniers chapitres portent essentiellement sur des descriptions de types spécifiques de ressources d'essai et sur la manière dont on peut les associer pour simuler des conditions opérationnelles prédites. Un catalogue non exhaustif de Centres d'essai de GE utiles est inclus en annexe de ce manuel.

La version d'origine de ce manuel a été mise à jour pour apporter des détails supplémentaires à des traitements antérieurs, tout en présentant de nouveaux supports et en exploitant plus largement les données chiffrées afin de faciliter la compréhension. Les nouveaux supports incluent des discussions relatives aux E&E des systèmes de contre-mesures infrarouges, systèmes de leurre à radiofréquences remorqué, systèmes furtifs et armes à énergie dirigée (hyperfréquences à grande puissance [HPM] et laser à énergie élevée [HEL]). Les chapitres traitant des ressources d'E&E, de la modélisation et de la simulation, ainsi que de l'expérience acquise, ont été mis à jour pour tenir compte des avancées des dix dernières années. L'annexe proposant un échantillon des centres d'E&E de GE des Etats membres a également été mise à jour.

Acknowledgements

The authors of this update acknowledge the stalwart efforts of the editors, H. Banks and R. McQuillan, and the many contributors to the original version of this Handbook. That version has already stood the test of time, having been a useful and widely available reference work for more than a decade for those active in the field of EW T&E – engineers, managers, researchers, academics and those new to EW. The original version has formed an excellent and solid basis for this update, with some sections requiring only minor amendments – indeed a testament to the knowledge and wisdom of the original authors.

Acknowledgement is given to contributors to this update, especially the agencies and companies who have kindly provided the photographs that the co-authors hope will make this update more informative than its predecessor. The authors are grateful for the guidance and assistance of Mr. Carter Wilkinson, FT3 Champion for SCI-203, and for the FT3 Group's comments on the drafts of the update, especially those of Mr. Bertil Gustavsson (Swedish FMV: Test & Evaluation's Chief Flight Test Engineer). Thanks also go to the following, whose assistance has helped the co-authors during this three-year SCI-203 tasking: Mr. Mitch Midgley-Davies (EW Test Facility), Mrs. Alison Heminsley (Head of M&S), Mr. Tony Shields (Systems Test Department) and Mr. Ian MacDiarmid (Head of Electromagnetics), all of BAE SYSTEMS – Military Air and Information. Thanks for input also go to Mr. Gordon Slater (Slater Aerosystems Ltd.).

The authors would also like to thank Mr. Steve Ruthven, Ms. Theresa Pham, Mr. Mario Dorado, and Mr. David Krohman of the 412th EW Group for their thorough review of the document and helpful suggestions. Mr. Lyndell Brown's (Tybrin Corporation) expertise and contribution to the High-Power Microwave and High Energy Lasers section was invaluable and is greatly appreciated. The technical editing support provided by Ms. Terressa Schmitz (JT3 Corporation) and Ms. Carolyn Rogers (JT3 Corporation) of the 412th Test Wing was also extremely helpful and is greatly appreciated.

The authors also acknowledge permission to use some material from prior publications by M. Pywell: the Institution of Engineering and Technology, Wiley & Sons (Encyclopedia of Aerospace Engineering) and the Royal Aeronautical Society.

Finally, the co-authors would like to thank their agencies, the U.S. Air Force Flight Test Center and BAE Systems (Military Air and Information), for support during the SCI-203 task to update this Handbook.

Foreword

While other volumes in the Flight Test Techniques Series have provided limited coverage of Electronic Warfare (EW) system testing, they have been generally aimed at a broad view of test and evaluation (T&E) and have not resulted in a singular, focused handbook on EW test techniques. This volume has as its sole focus the processes, techniques, facilities, and goals of T&E of modern EW systems. Much of the world of EW remains shrouded in secrecy, and detailed descriptions of some test resources, test results, and EW techniques cannot be presented herein. However, this volume can fulfil its desired goal of serving as a comprehensive introduction to the practice of EW test.

The first chapter provides a historical perspective of EW system development, an overview of EW systems, and basic motivations for T&E. The reader will quickly realise that the development and eventual qualification of EW systems is heavily reliant on the use of ground-based T&E resources. Since EW system performance is substantially scenario-dependent, much of the testing must be accomplished in a combat-representative electromagnetic environment. These high density and wildly dynamic conditions can only be offered to the tester through the application of complex models, simulations, and analytical processes.

Chapters 2, 3, and 4 of this handbook examine the motivation for testing each of the three primary classes of EW systems: EW Support Systems, Electronic Attack Systems, and Electronic Protect Systems. The characteristics of each type of system are discussed and examples of test objectives, measures of performance (MOPs) (a more detailed discussion of MOPs has been included as Annex B), and test resource utilisation are discussed. Chapter 5 introduces architectural considerations for EW Systems and discusses how various architectures may affect the test approach.

The EW Test Process, defined in Chapter 1, is based on an organised application of test resources including measurement facilities, models, simulations, hardware-in-the-loop facilities, installed system test facilities, and open air ranges. Chapter 6 describes the EW T&E resource types in detail, while Chapter 7 covers the important topic of modelling and simulation and threat simulation. EW T&E mission execution is complex and expensive and Chapter 8 describes the essential elements of EW flight test planning, execution and operations. Finally, some lessons learned in the T&E of EW systems have been collected in Chapter 9. While the specific issues depicted by these anecdotes may not be present in some future test programme, the general nature of the lessons may be useful in avoiding costly, time-consuming and often preventable problems.

This handbook also includes five Annexes. Annex A is a catalogue of some NATO EW Test Facilities. Annex B provides an enhanced discussion of MOPs and related test considerations. Annex C shows the derivation of the jam-to-signal ratio for two important cases. Annex D provides a Glossary and Annex E lists previous 160 and 300 series AGARDograph publications.

Overall, this handbook will help the novice EW tester become familiar with the major elements of EW T&E. More experienced testers will find the handbook to be a helpful reference source with a concise description of both test processes and test resources throughout the U.S. and Europe. For those individuals with broader responsibilities in the acquisition, operations, or sustainment of EW systems, this volume will be a useful introduction to the potential for gaining in-depth understanding of EW system functionality and performance through the disciplined application of the EW test process.

Preface

Mr. Martin Welch is a technical expert for 412th Electronic Warfare Group at the U.S. Air Force Flight Test Center, at Edwards AFB, California. He has been involved in the T&E of avionics, EW systems, and aircraft survivability technologies for 27 years. Since 2001, he has also served as the Director of the 412th EW Group's EW T&E University where he has played an instrumental role in educating the next generation of EW T&E professionals. He has been involved with the T&E of numerous radio frequency and infrared countermeasures systems as well as low observable and aircraft survivability technologies on a variety of platforms including the MC-130H Combat Talon II, AC-130U gunship, F-16, B-2A, and the F-117A.

Mr. Welch received Bachelor of Science degrees in Aerospace and Mechanical Engineering from Tri-State University in Angola, Indiana and a Master of Science degree in Electrical Engineering from the U.S. Naval Postgraduate School in Monterey, CA. Mr. Welch is also a graduate (by correspondence) of the USAF Air Command and Staff College and the Air War College.

Mr. Mike Pywell is an EW Technologist in the Electromagnetic Engineering Department at BAE Systems – Military Air and Information Division, U.K. He has been involved in T&E of avionics, EW systems, and survivability technologies for 37 years, and is an internationally recognised expert on RF threat simulators. For seven years he was also the Unit's RF and Laser Safety Officer, and for 11 years was also the division's EW Technology Programme Manager. He has been involved with T&E of Defensive Aids and RF communications systems on a number of platform types, and has an extensive background in electromagnetic interference and compatibility. He was a key player in the design of the company's aircraft-sized EW Test Facility and, more recently, led the multi-£M project to update its instrumentation.

For over 13 years he has represented the U.K. and his company on various NATO activities, including NATO Research and Technology Organisation (RTO) Studies SAS-011 (*Requirements and Options for Future NATO EW Capabilities*) and SAS-064 (*Update of Requirements and Options for Future NATO Airborne EW Capabilities*), and NATO Industrial Advisory Group (NIAG) Study Groups SG-66 (*Future Electronic Support System – Digital Solutions*), SG-79 (*Emitter Location and Data Links to facilitate Suppression of Enemy Air Defence*), and SG-105 (*Self-Protection interoperability (Flare/Chaff) for Aircraft and UAVs*). He has written several peer-reviewed journal and conference papers on Survivability and EW topics, and in 2007 won a Written Paper Prize (Silver Award) from the U.K.'s Royal Aeronautical Society. In 2010, he had two invited chapters published in the Encyclopedia of Aerospace Engineering: '*Electronic Warfare and Defensive Aids Systems Design and Development*' and '*Design Aspects of Aircraft Vulnerability*'.

Mr. Pywell received a Bachelor of Science degree in Electrical and Electronic Engineering from Coventry University and a Master of Philosophy degree from the University of Central Lancashire, where he has been a Senior Visiting Research Fellow since 2004. He is a Chartered Engineer and a Fellow of the Institution of Engineering and Technology.

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List of Acronyms and Symbols

1-v-1	1-versus-1
a.k.a.	also known as
AAA	Anti-Aircraft Artillery
AAP	Allied Administrative Publication
AATF	Aircraft Anechoic Test Facility
ABL	Airborne Laser
ABSTIRRS	Airborne Staring Infrared Radiometric System
ACETEF	Air Combat Environment Test & Evaluation Facility
ACMI	Air Combat Maneuvering Instrumentation
ADC	Analogue-to-Digital Converter
Ae	Effective Aperture
AFB	Air Force Base
AGARD	Advisory Group for Aerospace Research and Development
AGL	Above Ground Level
AI	Airborne Interceptor / Avionic Integration
AIDEWS	Advanced Integrated Defensive Electronics System
AM	Amplitude Modulation
AMES	Advanced Multiple Emitter Simulator
AMIRS	Advanced Millimeter Wave Imaging System
Amp	Amplitude, Amplifier
AoA, AOA	Angle-of-Arrival, Analysis of Alternatives
ARM	Anti-Radiation Missiles
ASC	Anechoic Shielded Chamber
ASE	Aircraft Survivability Equipment
ASIL	Advanced System Integration Laboratory
ASIMS	Airborne Spectral Infrared Measurement System
ASTE	Advanced Strategic and Tactical Expendables
ATIMS III	Airborne Turret IR Measurement System III
ATIRCM	Advanced Threat Infrared Countermeasures System
AVGPO	Anti-Velocity Gate Pull Off
AWSEM	Airborne Weapon System Engagement Model
BAF	Benefield Anechoic Facility
BC	Bus Controller
BE	Boundary Element
BEM	Boundary Element Method
BIT	Built-In Test
©	Copyrighted
C&D	Controls and Displays
C3I	Command, Control, Communication, and Intelligence
CAD	Computer-Aided Design
CCM	Center for Countermeasures
CCTV	Closed Circuit Television
CCU	Cockpit Control Unit
CE	Conducted Emissions
CEESIM	Combat Electromagnetic Environment Simulator
CEM	Computational EM Modelling

CHAMP	Composite Hard-body And Missile Plume
CIGARS	Calibrated Infrared Ground/Airborne Radiometric System
Cm	Centimeter
CM	Countermeasures
CMDS	Countermeasures Systems
CNI	Communication, Navigation, Identification
COI	Critical Operational Issues
COMINT	Communications Intelligence
COMSEC	Communications Security
CONOPS	Concepts Of Operation
CONSCAN	Conical Scan
CROSSBOW	Construction of a Radar to Operationally Simulate Signals Believed to Originate Worldwide
CRT	Cathode Ray Tube
CS	Conducted Susceptibility
CTP	Critical Technical Parameter
CW	Continuous Wave
D&D	Design and Development
DAP	Data Analysis Plan
DAS	Defensive Aids Suite/System
dB	decibel
dBm	decibel (referenced to a milliWatt)
dBW	decibel (referenced to a Watt)
DE	Directed Energy
Deg	Degrees
DEWSIM	Directed Energy Weapons Simulator
DF	Direction Finding
DIADS	Digital Integrated Air Defence System
DIRCM	Directed Infrared Countermeasures
DOA	Direction Of Arrival
DoD	Department of Defense
DRFM	Digital RF Memory
DRG	Defence Research Group
DSM	Digital Signal Model
DSTL	Defence Science and Technology Laboratory
DT&E	Developmental Test and Evaluation
E3	Electromagnetic Environmental Effects
EA	Electronic Attack
EC	Electronic Combat
ECCM	Electronic Counter Countermeasures
ECM	Electronic Countermeasures
ECR	Electronic Combat Range
ECSEL	EC Systems Evaluation Laboratory
ELINT	Electronic Intelligence
ELS	Emitter Locating System
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMCON	Emission Control
EMH	Electromagnetic Hazards
EMI	Electromagnetic Interference
EMMLS	Eglin Mobile Missile Launcher System

EMP	Electromagnetic Pulse
EO	Electro-Optical
EP	Electronic Protection
ERP	Effective Radiated Power
ES	EW Support
ESD	Electro-Static Discharge
ESM	Electronic Support Measures
EW	Electronic Warfare
EWC	Electronic Warfare Chamber
EWCC	Electronic Warfare Coordination Cell
EWS	EW Support
EWsT	EW Simulation Technology
EWTF	EW Test Facility
EXCM	Expendable Countermeasures
F	Fahrenheit
FCR	Fire Control Radar
FDTD	Finite Difference Time Domain
FEM	Finite Elements Model
FLIR	Forward Looking Infrared
FMM	Fast Multi-Pole Method
FOTD	Fibre Optic Towed Decoys
ft	Feet
FTEC	Flight Test Editorial Committee
FTTG	Flight Test Techniques Group
FVP	Flight Vehicle integration Panel
G	Gain
GCI	Ground Controlled Intercept
GHz	Gigahertz
G_J	Antenna Gain (Jammer)
GO	Geometrical Optical
GPS	Global Positioning System
G_R	Antenna Gain (Radar)
G_{R-SL}	Antenna Gain (Radar Sidelobe)
GSE	Ground Support Equipment
GTD/UTD	General and Uniform Theory of Diffraction
GWEF	Guided Weapons Evaluation Facility
HARM	High-Speed Anti-Radiation Missile
HEL	High Energy Laser
HEMP	High-Altitude Electromagnetic Pulse
HF	Hostile Fire
HIRF, HiRF	High Intensity Radiated Field
HITL	Hardware-In-The-Loop
HLA	High Level Architecture
HPM	High-Powered Microwave
HPRF	High Pulse Repetition Frequency
HUD	Head Up Display
IADS	Integrated Air Defence System
IC	Integrated Circuit
IEEE	[US] Institute of Electrical and Electronics Engineers

IF	Intermediate Frequency
IFAST	Integration Facility for Avionic Systems Testing
IFM	Instantaneous Frequency Measurement
IR	Infrared
IRCM	Infrared Countermeasures
ISAR	Inverse Synthetic Aperture Radar
ISTAR	Intelligence Surveillance Targeting And Reconnaissance
ISTF	Installed System Test Facilities
J/S	Jamming-to-Signal ratio
JEWCS	[NATO] Joint EW Core Staff
JMITS	Joint Mobile Infrared Countermeasures Test System
J-PRIMES	Joint-Prefight Integration of Munitions and Electronic Systems
JSF	Joint Strike Fighter
JTE	Joint Threat Emitter
kHz	Kilohertz
kW	Kilowatt
L	Loss
LAIRCM	Large Aircraft IR Countermeasures
LEPO	Large Element Physical Optics
LLSC	Low Level Swept Characterisation
LO	Low Observable
LPF	Low Pass Filter
LPRF	Low Pulse Repetition Frequency
LRU	Line Replaceable Unit
LWIR	Long Wavelength IR
LWS	Laser Warning System
m	Meter
M&S	Modelling and Simulation
MALD	Miniature Air-Launched Decoy
MANPADS	Man-Portable Air Defence Systems
MAW	Missile Approach Warners
MC	NATO Military Committee
MC	Mission Computer
MDF	Mission Data Files
MDS	Minimum Discernable Signal
MERAJS	Millimeter Wave Emitters, Radars, and Jamming System
MF	Measurement Facilities
MFD	Multi-Function Display
MFS	Manned Flight Simulation
MG	Missile Guidance
MHz	Megahertz
MIJA	Mobile Intercept Jamming Assets
MLAW	Missile Launch and Approach Warners
MLFMM	Multi-Level Fast Multiple Method
MMI	Man-Machine Interfaces
MMW	Millimeter Wave
MNF	Multi-National Force
MoD	Ministry of Defence
MOE	Measures Of Effectiveness

MoM	Method of Moments
MOP	Measures Of Performance
MOS	Measures Of Suitability
MPRF	Medium Pulse Repetition Frequency
MROCS	Millimeter Wave Obscurant Characterization System
MRV	Mini-Radar Van
MS&SE	Modelling, Simulation and Synthetic Environments
MWIR	Mid-Wavelength IR
MWS	Missile Warning System
NATO	North Atlantic Treaty Organization
NEDB	NATO Emitter Database
NEWVAN	NATO EW Van
NIAG	NATO Industrial Advisory Group
NMSG	NATO Modelling and Simulation Group
NRL	Navy Research Laboratory
NSRL	NATO Simulation Resource Library
OAR	Open Air Range
OCC	Operations Control Center
OE	Operational Effectiveness
OFP	Operational Flight Program
OPSEC	Operational Security
OS	Operational Suitability
OT	Operational Test
OT&E	Operational Test and Evaluation
PC	Personal Computer
PDW	Pulse Descriptor Word
P_e	Probability of Effect
PID	Program Introduction Document
P_J	Jammer Transmitter Power
P_k	Probability of kill
PO	Physical Optical
PPI	Plan Position Indicator
P_R	Radar Transmitter Power
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Intervals
PSI	Platform Systems Integrator
PSSSEF	Portable Seeker/Sensor/Signature Evaluation Facility
PTC	Planned Test Condition
PTD	Physical Theory of Diffraction
PW	Pulse Width
R	Range
R&D	Research and Development
RAM	Radar Absorbent Material
RCIED	Radio-Controlled Improvised Explosive Device
RCS	Radar Cross Section
RE	Radiated Emissions
RF	Radio/Radar Frequency
RFCM	RF Countermeasures System
RiL	Reduction in Lethality

RiS	Reduction in Shot Opportunities
RISS	Real-time IR Scene Simulator
RMS	Root Mean Squared
ROE	Rules Of Engagement
RS	Radiated Susceptibility
RTA	Research and Technology Agency
RTB	Research and Technology Board
RTCHAMP	Real Time Composite Hard-body And Missile Plume
RTO	Research and Technology Organisation
RWR	Radar Warning Receiver
SAD	Short-Range Air Defence Site Simulator
SAM	Surface-to-Air Missile
SAR	Synthetic Aperture Radar
SBR	Shooting Bouncing Ray
SCR	Shielded Control Room
SE	Survivability Equipment
Sec	Seconds
SI	System Integration
SIGINT	Signals Intelligence
SIL	Systems Integration Laboratory
SMA	Sub-Miniature A
SMS	Signal Measurement System
SOC	Statement of Capability
SOJ	Stand-Off Jamming, Jammer
SPIRTS	Spectral and In-band Radiometric Imaging of Targets and Scenes
SPJ	Self-Protection Jamming, Jammer
SS	Sub-System
SSA	Solid State Amplifier
SSL	Solid-State Lasers
STANAG	[NATO] STANdardisation AGreement
STEF	Seeker Test & Evaluation Facility
STIRRS	Staring Infrared Radiometric System
STV	Seeker Test Van
SUT	System Under Test
T&E	Test and Evaluation
TC	Test Conductor
TD	Test Director
TEL	Transporter-Erector-Launcher
TGP	Targeting Pod
TIGER	Threat IR Generic Emulation Radiometer
TLM	Transmission Line Method
TM	Telemetry
TRACSVAN (TV)	Transportable Radar and Communications Jamming and Simulation Vans TV
TSPI	Time-Space-Positioning Information
TT	Target Tracking [radar]
TTI	Time To Impact
TWS	Track While Scan
TWTA	Travelling Wave Tube Amplifier
U.K.	United Kingdom
U.S.	United States

UAS	Unmanned Aerospace/Autonomous System
UAV	Unmanned Aerospace Vehicle
UCAS, UCAV	Unmanned Combat Air/Autonomous System/Vehicle
USA	United States of America
USAF	United States Air Force
UTD	Uniform Theory of Diffraction
UV	Ultraviolet
V&V	Verification and Validation
VGPO	Velocity Gate Pull-Off
VV&A	Verification, Validation and Accreditation
WPNS	Weapons
WRA	Weapon Replacement Assembly
σ	Radar cross-section

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Chapter 1 – INTRODUCTION TO EW TEST AND EVALUATION

1.1 PURPOSE AND SCOPE

This AGARDograph, which supersedes the original version (Volume 17, Issue 1, 2000), provides an overview of Electronic Warfare (EW) Test and Evaluation (T&E). This Handbook's primary purposes may be stated as:

- To introduce the novice to a disciplined approach to EW testing.
- To provide a concise reference for the EW T&E process and test resources for more experienced testers and programme managers.
- To aid NATO Nations in meeting the affordability challenges facing them. Failure to evaluate installed EW system performance adequately on the ground typically results in significantly increased flight test cost and lengthened schedules.
- To catalogue current T&E resources and capabilities available within NATO Nations (Annex A).

The Handbook offers guidance in applying available resources to meet identified test objectives and to aid cost-effective satisfaction of contractual and operational requirements.

Some caveats apply to this Handbook:

- EW systems and consequently T&E equipment operate in the same technical parameter space, since all operate generally with the same multi-spectral threat environment.
- This Handbook has been predominantly updated by its lead co-authors, who are US and UK EW Specialists. As a result, some unintentional US/UK bias may be detected by the reader. These co-authors are well aware that national variations exist in a number of areas across the Handbook and that differing views exist internationally on the relative importance of items and process elements described therein. The co-authors consider that when taken as a whole, this Handbook is sufficiently robust as a NATO-wide document and that any national differences can be adequately handled by each Nation's EW Experts. The co-authors welcome any comments that readers may have on the Handbook, with a view to inclusion in future updates.
- All system types are covered for EW T&E capabilities, but the concentration is on Radio/Radar Frequency (RF) and Infrared (IR) systems operating in EW frequency ranges.
- No requirement or numeric in the Handbook is intended to be associated with any specific System Under Test (SUT), platform or programme.
- Emitter databases, essential to EW systems and associated T&E equipment, are not discussed since they are nationally sensitive. For the same reason there is limited discussion of Low Observability (a.k.a. 'Stealth' or 'electromagnetic signatures') and directed energy weapons, although, where possible, a fuller discourse on their T&E is provided.
- All images and references to T&E facilities and resources are provided as examples only. They do not indicate that any one facility, resource or equipment is any better than another. Their inclusion in this Handbook does not constitute recommendation by the authors.
- The EW T&E engineer, armed with information in this Handbook, remains responsible for the timely identification, planning and execution of cost-effective tests, using appropriate facilities and resources, in order to satisfy their programme's requirements.

1.2 BACKGROUND

Developing and fielding modern EW systems is complex, expensive, and requires a disciplined test approach to ensure that limited programme resources are prudently applied. Therefore, an EW T&E professional's most important task is to determine the appropriate test objectives to satisfy the acquisition programme requirements. All acquisition programmes have milestones where system performance must be evaluated to determine if the system is ready to proceed to the next phase. Decision makers need timely and accurate information about the SUT. Test programmes should be structured such that they provide decision-quality information incrementally throughout the life of the test programme. This allows for system deficiencies to be identified early in the programme when the costs to resolve them are relatively low.

The scope of EW test programmes can vary greatly and it is the task of the EW T&E professional to construct a test programme to cost-effectively meet the programme needs. There are a wide variety of test resources and techniques available to accomplish this. A simple programme might entail taking a radar warning receiver of the type that has been previously proven on a fighter platform and re-hosting it on a transport aircraft. At the other end of the spectrum are programmes with several new EW systems operating as an integrated suite on a platform that is itself networked with other systems. In both cases, the EW T&E professional's task is to tailor a programme that tests the right things at the right time using the right resources.

This Handbook also provides a useful directory of key EW T&E resources available to NATO members, and examines lessons of the past which can be used to improve the productivity of future testing. While much of the content is aimed at personnel with relatively little experience in the field of EW T&E, this volume can also serve as a basic checklist of issues to be covered in planning, conducting, and evaluating EW tests. In order to gain an appreciation for current practices in EW T&E, some discussion of the history of EW system development, EW system application in modern warfare, and generic elements of disciplined testing are presented in this introduction.

With the rapid evolution of military electronics and computer science, the range, complexity, and sophistication of EW systems has grown significantly. This Handbook focuses on testing avionics systems for military aircraft, the primary purpose of which is Electronic Countermeasures (ECM) and Counter-Countermeasures (ECCM). This testing has much in common with the testing of any avionics system, especially in those areas that relate to availability, operability, supportability, and reliability.

1.3 HISTORY OF EW

Many would argue that EW dates back to the Crimean War and American Civil War and the advent of the telegraph as an important form of military communications. Early EW techniques included interruption of the enemy's communications by cutting the telegraph lines, and deceiving the recipients by sending misleading messages. These processes are similar to the current concept of Electronic Attack (EA). Listening in on the enemy's transmissions by tapping the telegraph lines may be the earliest form of EW Support (ES). While no radiated Electromagnetic (EM) energy was involved at this point, the rudimentary concepts of attacking, protecting, and exploiting electronic communications had begun. [1]

The pursuit of EW in military aviation first began in earnest during World War II. Radio beams were used to guide bombers to their targets; radar was used to detect and locate enemy aircraft; and radio communication was becoming the primary means of establishing command and control. As each new electronic measure was employed, the adversary developed a countermeasure or EA capability. In many instances, in order to preserve the advantage of the initial electronic measure in the face of countermeasures, counter-countermeasures or Electronic Protection (EP) were developed. [2]

One of the most significant EW events during World War II and one that highlights EW's role as a force multiplier was the first use of 'Window' by the British during a bombing raid on Hamburg in July 1943.

'Window' was the code name for an early version of chaff. The British had been encountering heavy losses from radar-directed German anti-aircraft guns and night fighters. The use of 'Window' totally surprised the Germans and completely disrupted the German gun direction and fighter control radars resulting in significantly reduced losses and the near complete destruction of Hamburg. [3]

The Vietnam War, with the backdrop of the Cold War, presented the next major flurry of EW activity. The North Vietnamese employed a Soviet-style Integrated Air Defence System (IADS). Throughout the war the North Vietnamese continued to upgrade the IADS and correspondingly the U.S. adapted to the upgrades with new countermeasures. While strategic bomber and reconnaissance aircraft have long used EW equipment such as Radar Warning Receivers (RWR) and Self-Protection Jammers (SPJ), Vietnam led to widespread use of these systems on tactical aircraft. The conflict also led to the development of specialised aircraft known as Wild Weasels to suppress enemy Surface-to-Air Missile (SAM) radars. The Wild Weasels employed sophisticated EW receivers and Anti-Radiation Missiles (ARMs) to accomplish their mission. Figure 1-1 shows an SA-2 Guideline missile of the type commonly used in Vietnam and an F-105G Wild Weasel aircraft. This era marked the beginning of modern requirements for survival in the presence of electronically-directed enemy fire control. [4]

Figure 1-1: SA-2 GUIDELINE Missile (top); F-105G Wild Weasel Aircraft with a Shrike ARM (bottom) – (U.S. DoD and USAF Photos).

The Arab-Israeli War in October 1973 provides a good illustration of what happens when the air defence threat posed by one adversary advances beyond the EW capabilities of the other. The war "lasted less than a month, yet it contained all the elements of a much longer war. It was an intense, bitterly contested conflict with each side well-equipped with the weapons for modern warfare. The Egyptian and Syrian air defences at that time, were developed from Soviet design. The design stressed overlapping networks of SAM and Anti-Aircraft Artillery (AAA) coverage. This formidable air defence network consisted of the SA-2, SA-3, SA-6, SA-7, the ZSU-23-4, and other AAA systems. While there were proven ECM from the Vietnam War for the SA-2 and SA-3 and IR countermeasures, such as flares for the SA-7, the SA-6 proved to be a surprise. The SA-6's radars operated in a portion of the electromagnetic spectrum never used before by the Soviets. The Israelis tried to compensate for their lack of ECM against the SA-6 by flying lower, trying to get under its radar coverage. This tactic placed them into the heart of the ZSU-23-4 threat envelope and contributed to the loss of numerous aircraft. This forced the Israelis to adjust their electronic equipment, modify their tactics, and seek additional ECM equipment, such as ECM pods and chaff dispensers from the U.S. However, before the tactics were changed and the new equipment arrived, the Israelis suffered heavy aircraft losses, which taught them a valuable lesson." [5]

The 1970s and 1980s also saw the coming of age of Low Observable (LO) technology. While LO principles have been applied earlier, the F-117A development marked the first time that LO principles would be the dominant design attribute for an aircraft. The F-117A, shown in Figure 1-2, became operational in 1985 and played a key role in Operation Desert Storm, where it operated with impunity in heavily defended airspace. Since the F-117A debut, LO technology has become an important consideration for all combat aircraft. [6]

Figure 1-2: F-117A Nighthawk: The First Operational Low Observable Aircraft – (U.S. DoD Photo).

Operation Desert Storm (1991) was spearheaded by an effort to suppress and destroy the Iraqi Kari IADS. This effort brought together all aspects of EW. Air-launched decoys deceived the Iraqi IADS into engaging them with radar-directed SAM systems such that Wild Weasel aircraft could target them with

High-speed ARMs (HARM). Support jamming aircraft jammed surveillance radars. F-117A aircraft attacked and destroyed key Command, Control, and Communications (C3) centres supporting the IADS. This initial coordinated EW activity was crucial to success of the ensuing coalition air campaign. [7]

Much of the historical EW perspective is still relevant to the modern electronic battlefield. What have changed are the speed, engagement range, communications network robustness, and lethality of the modern threat. The EW community must stay abreast of developments in the threat environment to ensure that aircrew do not face the type of surprises that the Israelis faced in 1973.

1.4 EW DEFINITIONS AND SYSTEM CLASSIFICATION

This section defines EW and related terms and describes the different classifications of EW suite architecture.

1.4.1 EW and Related Definitions

The definition of EW is broadly the same internationally, although EW components' definitions differ between NATO and some of its member and partner Nations. EW is defined in NATO as: 'Military action to exploit the electromagnetic spectrum encompassing: the search for, interception and identification of electromagnetic emissions, the employment of electromagnetic energy, including directed energy, to reduce or prevent hostile use of the electromagnetic spectrum, and actions to ensure its effective use by friendly forces.' [8]

The definition of EW does not make any reference to the equipment used, but rather is confined to a description of the task or mission. For the most part, the equipment used specifically in the accomplishment of EW is avionics. This relationship between EW and avionics establishes the domain of EW T&E in the aerospace environment. Testing and evaluating EW systems requires the application of the skills and insights requisite of testing avionics equipment in general, tempered with a view of the military actions to be accomplished using these devices. The functionality and military worth of EW systems is highly role, mission, and scenario dependent.

The U.S. Chairman of the Joint Chiefs of Staff, Joint Publication (JP) 3-13.1 addresses EW operational applications and also considers multi-national EW coordination. This document notes that while "'NATO Electronic Warfare policy' is largely based on US EW policy, the perspective and procedures of a Multi-National Force (MNF) EW Coordination Cell (EWCC) will be new to most." [9] The reader is referred to the NATO documents: Military Committee document 64/9 and STANAG 6018, both Restricted documents, for further information regarding NATO definitions of EW and its components. [10],[11]. The U.S. definitions will be used throughout this document unless otherwise stated.

In the NATO and U.S. Joint lexicon, EW has three sub-divisions: EA, EP, and ES. While minor national variations exist across NATO and its partner Nations, this lexicon has typical definitions:

- Electronic Attack (EA) – The use of electromagnetic energy, DE, or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralising or destroying enemy combat capability and is considered a form of fires. [12]
- Electronic Protection (EP) – Actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy use of electromagnetic spectrum that degrade, neutralise, or destroy friendly combat capability. [13] EP is also known as ED, Electronic Defence.
- Electronic Warfare Support (ES) – Actions taken by, or under direct control, of an operational commander to search for, intercept, identify and locate, or localise sources of intentional and unintentional radiated electromagnetic energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations. [13]

Figure 1-3 shows the three EW sub-divisions and identifies some specific applications.

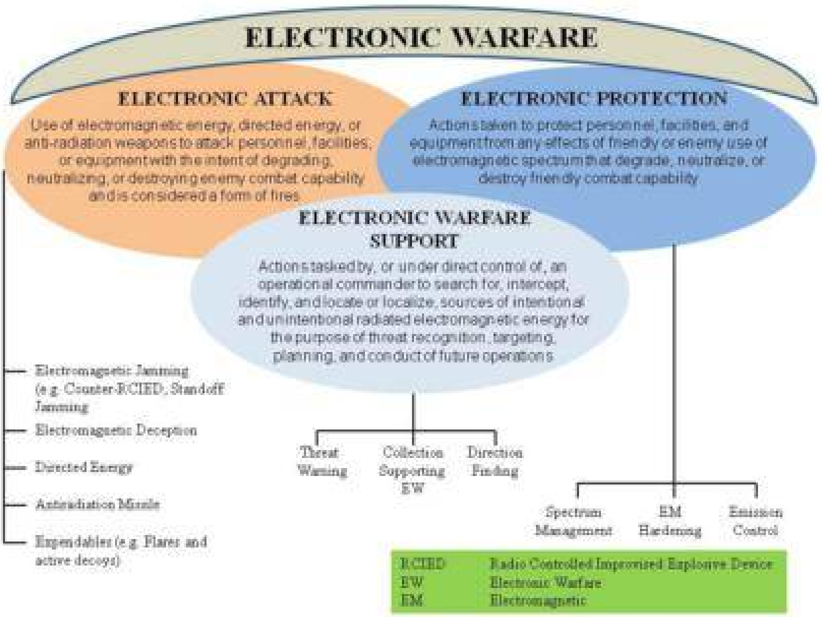

Figure 1-3: EW Sub-Divisions.

Electronic Intelligence (ELINT), Signals Intelligence (SIGINT), and Communications Intelligence (COMINT) have many similarities to ES. They are defined as:

- ELINT – Technical and geolocation intelligence derived from foreign non-communications electromagnetic radiations emanating from other than nuclear detonations or radioactive sources. [14]
- SIGINT – A category of intelligence comprising either individually or in combination all communications intelligence, electronic intelligence, and foreign instrumentation signals intelligence, however transmitted or intelligence derived from communications, electronic, and foreign instrumentation signals. [15]
- COMINT – Technical information and intelligence derived from foreign communications by other than the intended recipients. [16]

These mission areas are not considered EW under the US definition. However, the systems that perform these mission areas are functionally similar to ES systems and much of the information about ES systems and ES systems T&E in this Handbook applies to them as well.

1.4.2 EW System Architecture Classifications

There are a variety of EW system architectures in use, so it is difficult to separate them into neatly defined categories. Three general classifications, illustrated in Figure 1-4, will be used in this Handbook:

- **Stand Alone** – Each discrete EW system operates independently or nearly independently of every other EW system.

- **Federated** – Each EW system largely maintains its functional boundaries. The individual EW systems commonly share data via an EW data bus with the RWR serving as the bus controller. The individual EW systems also communicate via the avionics data bus to receive inputs such as aircraft attitude and flight data and to provide status information to the avionics system. The shared data also aids RF management; for example, the Fire Control Radar (FCR) can provide its operating characteristics such that the RWR and jammer will not process it as a threat.
- **Integrated** – All EW components, as well as other avionics systems, share common processing resources and databases. Data fusion algorithms are commonly used to enhance the information quality. Integrated systems can also schedule other aircraft system apertures and sensors to perform EW tasks, for example the FCR antenna is a high gain aperture capable of supporting secondary tasks. All controls and display information is routed by the central processor.

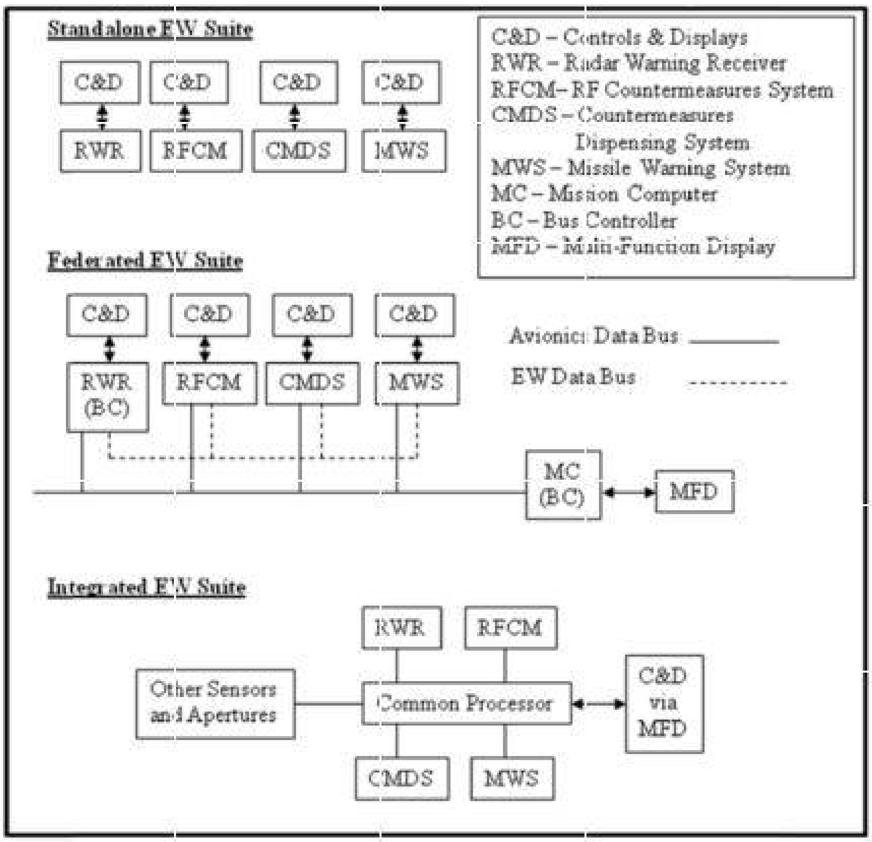

Figure 1-4: EW Suite Architecture Categories.

1.4.3 System Hierarchy

A weapon system is comprised of a number of elements. Table 1-1 identifies the individual elements and how they build up to form an entire weapon system.

Table 1-1: System Hierarchy.

Element	Description	Examples
Component	Constituent part of an LRU	• Circuit card assemblies
Line Replaceable Unit (LRU) also known as Weapon Replacement Assembly (WRA) or Module Replaceable Unit	An essential support item removed and replaced at field level to restore an end item to an operationally ready condition.	• RWR receiver assembly • RWR signal processor • RFCM transmitter
Equipment	A complete and functionally discrete piece of equipment	• RWR • RFCM System • MWS • CMDS
Sub-System	Comprised of the various equipments	• Defensive Aids Sub-System • Navigation Sub-System
System	Comprised of the various sub-systems	• Avionics System • Propulsion System
Weapon System	Comprised of the various systems	• Complete Aircraft

1.5 TEST RESOURCE CATEGORIES

EW system testing spans an enormous range starting with inspection of components and materials to be used in the manufacture of systems, and culminating with in-service support, including mission data and countermeasures validation and optimisation, problem investigation, and failure diagnosis. This Handbook concentrates on testing used to assess the capability of an EW system to comply with system-level specifications, perform its intended military role, and its potential to be serviceable and supportable in the field. These qualities are generally assessed using a combination of flight- and ground-based tests and employ a wide range of test resources.

Test resource categories applicable to EW testing include Measurement Facilities (MFs), System Integration Laboratories (SILs), Hardware-In-The-Loop (HITL) facilities, Installed System Test Facilities (ISTFs), and Open Air Ranges (OARs). A sixth resource category is Modelling and Simulation (M&S). See Figure 1-5.

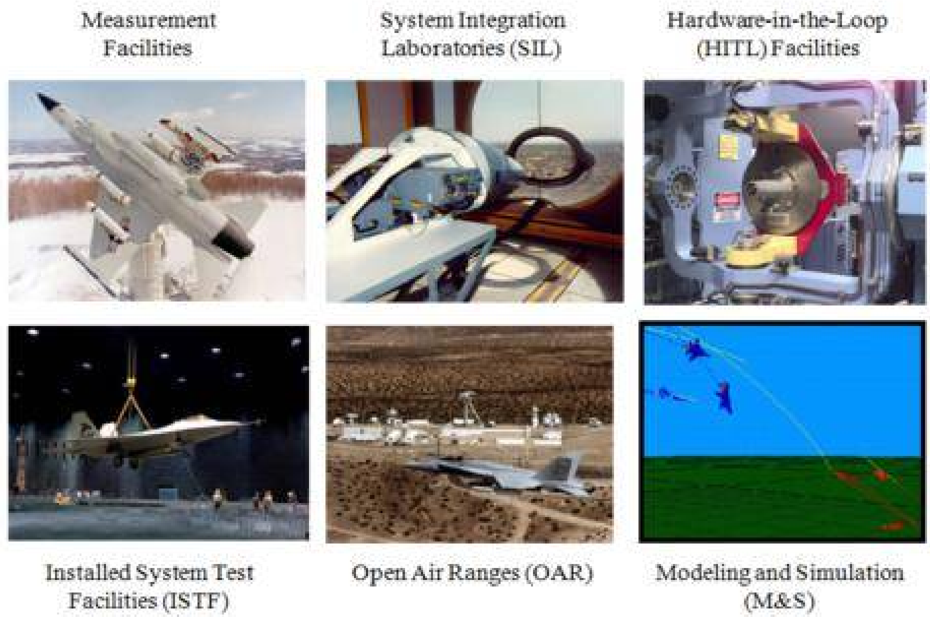

Figure 1-5: EW Test Resource Categories – (U.S. DoD Images).

It is tempting to equate 'types of tests' with specific test facilities. For instance, OARs provide an environment where aircraft can be operated in their intended flight regimes, and can often support testing of systems installed in the aircraft while the vehicle is on the ground. In this scenario, an 'installed system' type of test using an OAR resource category would be conducted.

Large anechoic chambers, capable of holding an actual aircraft, are frequently classed as Installed System Test Facilities. While this categorisation is applicable, it does not convey the full range of applications for which an ISTF may be suitable. Frequently, ISTFs are used to support HITL tests, integration activities, and simulations. If the resource category description is used to define the test types that the resource can support, there is a risk of inaccurate or incomplete understandings of the T&E value of many test resources.

This Handbook will use the term Test Resource Category to identify the primary role of a specific test facility and will use Test Type to reference the various levels of testing and system integration that may be accommodated at a given facility.

1.6 THE ACCEPTANCE PROCESS AND TYPES OF TEST

EW equipment manufacturers and Platform Systems Integrators (PSI) must ultimately prove that their system or systems meet the contractual specification requirements. The details of the process vary by country; however there are some common elements. The contractual requirements are typically tabulated in a matrix identifying the particular requirement, the acceptance method, and the venue for the activity. Table 1-2 identifies and defines the type of verification and the methods. [17]

Table 1-2: Verification Types and Methods.

TYPE	METHOD
Inspection	• Physical inspection, visual verification • Document review • Read-across by analogy, where prior evidence alone is used to fulfil a requirement
Analysis	• M&S, e.g., mathematical, statistical, physical • Read-across by evaluation, where prior evidence is used to partly fulfil a requirement • Technical evaluation of equations, charts, reduced and/or representative data
Test	• Laboratory – software test, rig test (by equipment manufacturer/supplier) and rig test (by manufacturer/supplier or Platform Systems Integrator – PSI) • Anechoic chamber (specialist equipment) • Aircraft ground test, e.g., Electromagnetic Compatibility and Interference (EMC/EMI) • Flight test – local or dedicated EW range
Demonstration	• Un-instrumented rig or aircraft test where requirement is met by observation alone

There is a hierarchy of test types which must take place in order to quantify the overall performance of the SUT. This sequence of T&E events tends to mirror the overall maturing of the SUT as it progresses through the development process.

Figure 1-6 depicts this process and helps to characterise an important attribute of the test process. It is a purposefully recursive process that continually refines the estimated performance of the SUT as it reaches higher levels of integration and maturity. Such a deliberate process may be difficult or even impossible to achieve due to fiscal, schedule, or test facility constraints. Each of the desired test events represents an opportunity to help reduce risk in developing the EW system. Here is where the tester's experience and application of statistically sound methods can construct a test programme that optimises the use of test resources while meeting budget and schedule constraints. Ultimately, the tester provides decision makers with quantifiable information about programme technical risks.

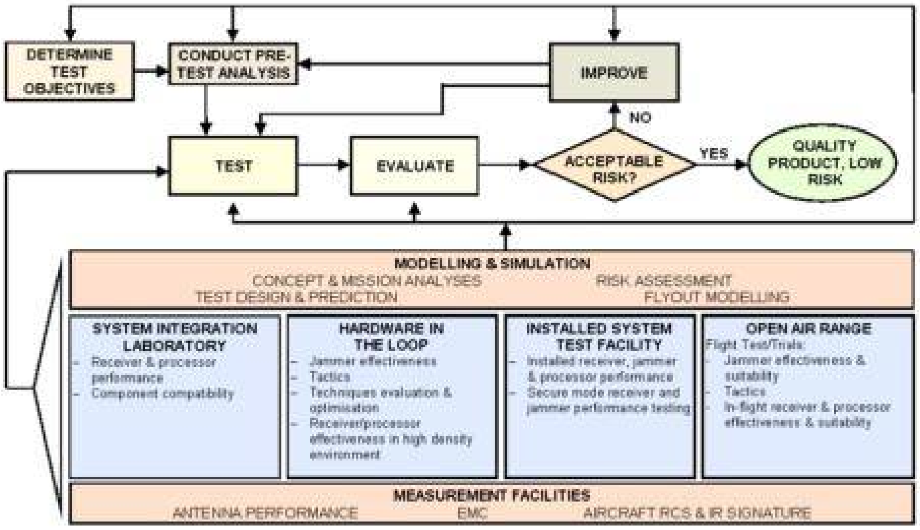

Figure 1-6: The EW T&E Process.

Some of the choices may not be obvious. For instance, flight testing is generally considered to be a more complete test than those events accomplished in an HITL or ISTF. The experienced tester, however, may determine that due to limitations of threat simulators available on the OAR, he can actually create a more realistic test scenario in an ISTF. This particular type of choice is frequently encountered when testing the effects of high threat or signal density. Most OARs are very limited in the quantity of threat simulators they can provide. On the other hand, HITLs and ISTFs can most often simulate very large numbers of threat signals with adequate fidelity.

1.7 EW SYSTEM APPLICATION IN WARFARE

As discussed earlier in this section, EW can be broken down into three primary divisions: EA, EP, and ES. While it is not the intent of this Handbook to fully describe the role of EW in military operations or to provide a detailed analysis of specific EW techniques, a brief overview of each of these primary divisions is given below to underpin a better understanding of the test requirements.

1.7.1 Overview of EA

EA is the use of electromagnetic or directed energy to attack personnel, facilities, or equipment. There are five basic sub-divisions of EA: jamming, deception, DE, ARM, and expendables. Jamming is generally defined as deliberate radiation, re-radiation, or reflection of energy for the purpose of preventing or reducing an enemy's effective use of the electromagnetic spectrum. With recent advances in technology and more frequent use of spectra outside the RF range, this definition can be extended to cover similar action against IR, Ultraviolet (UV), and electro-optical systems.

Jamming is the most prevalent form of EA and has two major sub-divisions: self-protection and support. In self-protection jamming, also known as defensive EA, the same vehicle being targeted by the enemy radar or sensor system carries the EA system. Support jamming, also known as offensive EA, has three sub-categories: stand-off, stand-in, and escort. In stand-off jamming, the EA platform normally operates beyond the engagement range of the enemy air defence system and jams the surveillance elements of the air defence system in support of other attacking aircraft. Stand-in jamming is similarly directed at the surveillance elements of an enemy air defence system, but operates within the range of enemy air defence weapons. Stand-in jamming is normally performed by Unmanned Air Systems (UAS)[1]. In escort jamming, the jamming aircraft accompanies the strike package it is charged with protecting. This means that the escort jamming aircraft must have performance and range similar to the strike aircraft.

There are basically two types of enemy radar that must be jammed by EA:

- Surveillance radars perform two basic functions in an IADS: early warning, which provides overall situational awareness for forming the air picture, and target acquisition for terminal threat systems.
- Radars associated with the terminal threat systems, typically those performing target tracking and missile guidance. Terminal threat radars are usually given high priority in the hierarchy of EA threats because they are associated with the lethal phases of a weapon guidance system.

EA jamming techniques are used to disrupt or break the threat's range, velocity, or angle tracking capability and force the threat system to re-acquire the target and re-aim the weapon – a process which could provide the target the time to pass harmlessly through the threat's engagement envelope.

EM deception is the deliberate radiation, re-radiation, alteration, suppression, absorption, denial enhancement, or reflection, of EM energy in a manner intended to convey misleading information to an enemy or to an enemy's EM-dependent weapons, thereby degrading or neutralising the enemy's combat capability.

DE is an umbrella term covering technologies that relate to the production of a beam of concentrated electromagnetic energy or atomic or sub-atomic particles. The two most common manifestations of DE are High-Energy Lasers (HELs) and High-Power Microwave (HPM) devices.

ARMs are designed to home on RF emissions from enemy radar systems. These missiles aim to either destroy the targeted radar system or at least force it to cease operating to avoid destruction. These air-launched weapons normally receive targeting information from ES receiver systems on board the host platform. It is beyond the scope of this Handbook, but it is important to realise that these and other weapons systems are increasingly able to tap into networked systems that can provide targeting information from other sources via data links.

Expendable countermeasures are deployed from a host platform and normally perform self-protection functions. The three most common expendable countermeasures types are chaff, flares, and towed decoys. Chaff can be employed against search radars or as self protection against Target-Tracking Radars (TTRs) and missile guidance radars. Chaff is dispensed in bundles composed of many thousands of very thin conductive elements designed to reflect RF energy and confuse the victim radar. Flares are designed to protect aircraft from IR-directed threat systems by providing a more attractive target to the missile seeker than the targeted aircraft. Towed decoys attempt to provide the threat system a more attractive target than the platform they protect.

In addition to the above elements of EA, Emission Control (EMCON)[2], and Low Observable (LO) techniques are considered passive forms of EA. [18]

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[1] UAS, which also means Unmanned *Autonomous* Systems, include UAVs (Unmanned Aerospace Vehicles) and UCAVs (Unmanned Combat Air Vehicles).

[2] EMCON is according to some sources a form of EP and will be treated as EP for the remainder of this handbook. [18]

1.7.2 Overview of EP

EP is that action taken to negate the effects of either enemy or friendly EA that would degrade, neutralise, or destroy friendly combat capability. EP techniques tend to be the result of developments of EA capabilities. Most EP techniques are defined in relation to how they counter a specific EA threat. Usually, the EP technique is some improvement in the sensor system design that counteracts the effect of a specific EA technique; therefore, it is difficult to understand the purpose of a specific EP technique without knowing the EA technique that it is designed to counteract. EMCON is also a form of EP. [19]

Usually, the design requirements of a system that operates in a jamming environment will exceed the requirements of a similar system designed to operate only in a friendly environment. For example, a radar receiver designed for use in a civilian environment can tolerate relatively wideband frequency response with only minimal degradation in performance. A similar receiver designed for use in a jamming environment would require narrowband frequency response to prevent skirt jamming.

The EP designer may utilise sophisticated transmitted waveforms and receiver processing that will make deception jamming difficult. This forces the enemy to use high-power, brute-force noise jamming. The EP designer can then use frequency hopping or multiple simultaneously transmitted frequencies so that the enemy must broaden the bandwidth of his jamming. This causes the enemy jammer to diffuse its energy over a wide bandwidth, thus reducing the effectiveness of the EA. A true, never-ending cat-and-mouse game between EA and EP designers then follows.

1.7.3 Overview of ES

ES is that division of EW concerned with the ability to search for, intercept, identify, and locate sources of radiated electromagnetic energy. ES is used in support of tactical operations for situational awareness, threat avoidance, homing, and targeting. Onboard radar warning and missile warning receivers, as well as many off-board surveillance systems, are considered elements of ES.

1.8 THE EW T&E PROCESS

The EW test process, as depicted in Figure 1-6, requires a disciplined approach to ensure that the required testing is accomplished in a timely and cost-effective manner that ultimately provides acquisition programme decision makers with accurate information about the SUT. The most important part of a test programme is determining the test objectives. The test objectives get to the heart of what is to be accomplished and thereby determine the direction and scope of the programme. If the test team doesn't get the objective right, the programme runs a significant risk of not generating the necessary information to support programmatic decision making. The test objectives need to be coordinated between programme management and the test team to ensure that all participants understand the relationship between the financial resources available and the quality of information provided. A vital role of professional testers is to convey risk assessments to programme managers when financial resources are constrained and advise them on options.

1.8.1 Test Objectives

Test objectives derive from two basic sources: documented operational requirements of the military end user and contractual specification requirements. Ideally, these would be identical, but they sometimes differ in practice. The system programme office charged with acquiring the weapons system typically contracts with the manufacturer to provide specific quantifiable data about the performance of the acquired system. Test professionals representing the government generally participate in the Developmental Test and Evaluation (DT&E) phase to provide the programme office with an independent evaluation of the weapons system's performance relative to specification requirements. DT&E is defined as any testing used to assist in the development and maturation of products, product elements, or manufacturing or support processes. It is also any engineering-type test used to verify status of technical progress, verify that design risks are minimised, substantiate achievement of contract technical performance, and certify readiness for initial Operational Testing (OT). Development tests generally require instrumentation and measurements and are accomplished by engineers, technicians, or soldier operator-maintainer test personnel in a controlled environment to facilitate failure analysis. [20]

Additionally, the DT&E community must address military utility aspects of the SUT performance that are not addressed by the specification requirements. The role of DT&E above and beyond specification compliance assessments reduces the risk of finding problems in Operational Test and Evaluation (OT&E) that could preclude fielding the weapon system.

OT&E is the field test, under realistic conditions, of any item (or key component) of weapons, equipment, or munitions for the purpose of determining the effectiveness and suitability of the weapons, equipment, or munitions for use in combat by typical military users; and the evaluation of the results of such tests. [21] Test programmes that coordinate DT&E and OT&E throughout the programme's life greatly enhance their chance of successfully completing OT&E and fielding the weapons system.

Large acquisition programmes typically have a hierarchy of test objectives. A large programme charged with acquiring a new airframe that employs a number of potentially integrated sub-systems might have as an overall test objective: "Evaluate the performance of the F-XX aircraft". It could then have subordinate level test objectives such as: "Evaluate the defensive avionics suite", or "Evaluate the fire control radar system", etc. Further, an objective to evaluate the EW systems of an aircraft could be broken down into its components: "Evaluate the RWR performance", "Evaluate the expendable countermeasures system", etc. A small programme might have only a single stand alone objective, such as "Evaluate the performance of a new countermeasures flare". In any event, it is important that the EW tester be aware of how test objectives fit into the overall test programme.

1.8.2 Test Design

The DT&E test designers must ensure that two questions are answered. First, the test must determine if the manufacturer has met each of the contractual specification requirements. Second, the system must be evaluated to determine if the military utility is adequate to proceed to dedicated OT&E. It is possible for a system to meet all specification requirements but have sufficient military utility deficiencies to preclude a release to begin dedicated OT&E. OT&E testing is conducted under operationally realistic conditions to determine if the system is effective and suitable.

Figure 1-7 shows the main elements of test design. The programme objectives address both the specification compliance and the military utility and once they have been established, the test team must determine the measures by which the system performance or effectiveness will be evaluated. These are known as Measures Of Performance (MOPs) and Measures Of Effectiveness (MOEs). The MOPs are generally more applicable to DT&E and are generally tied directly to contractual technical performance requirements while MOEs apply to OT&E. This Handbook primarily addresses DT&E and will use the term MOP generically when discussing performance measures.

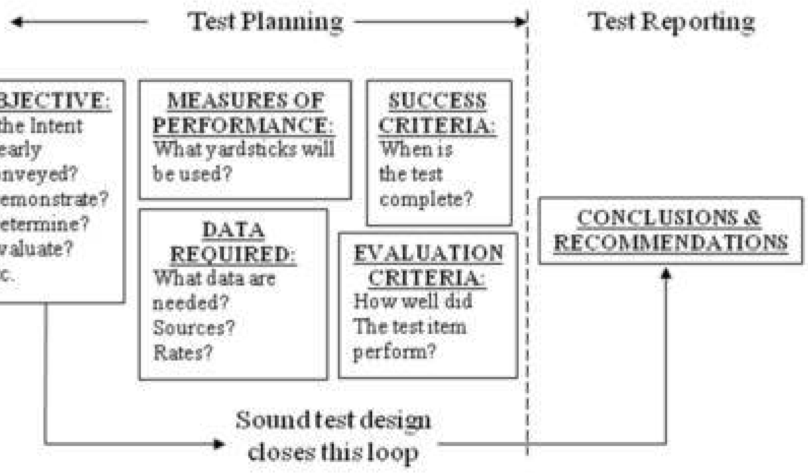

Figure 1-7: Test Design Elements.

The objectives must be testable, that is, the selected MOPs must be quantifiable attributes of the system that directly relate to operationally relevant functions. A specific type of MOP is the Critical Technical Parameter (CTP); the CTPs are parameters deemed vital to the desired capability of the weapon system. Two examples for an RWR include response time which relates directly to the warning time the system will provide the aircrew or angle of arrival measurement error which relates to the quality of the warning information provided. Note that MOPs are always nouns: time, error, etc.

Annex B discusses some common MOPs, to assist understanding measurements and what information they convey. It is intended to make the reader think about what details need to be addressed and documented in the planning stages, to avoid disagreements later in the programme when they are generally more difficult and costly to resolve.

System acquisition programme managers should involve experienced testers early in the system specification or contractual requirements development process. Experienced testers know what system attributes are meaningful, testable, and measurable. If a system attribute cannot be quantified or quantified in a useful manner, it is worthless.

Once the test objectives have been established and the MOPs identified, the amount of data required must be determined in order to estimate the values of the MOPs. This is critically important to programme managers because the amount will dictate the length and cost of the test programme.

Even the best designed tests only yield estimates of the true values of the SUT's measures of performance. MOPs are random variables generated from finite data samples. Therefore, it is impossible to establish the true value of a given MOP. A typical test will produce an estimate of the average value of an MOP, i.e., the mean or median and spread of the data, commonly expressed as the variance or the standard deviation. This means that each time a data set is collected it will produce a different result.

Many EW performance specifications are based on whether or not the estimated value of a MOP, such as response time, meets a required value. Even a well-conceived and executed test can result in a spread of the data collected. This implies that occasionally the estimated value will be sufficiently in error that the wrong conclusion about the system's performance may be drawn.

A key role that T&E professionals play on the acquisition team is to quantify the risk of such an error occurring and communicating that information to the decision makers prior to the test. This will ensure that decision makers understand the relationship between the resources expended and the quality of the answers that will be provided and ultimately the risk they will be accepting.

For example, if the response time contractual specification requirement for an RWR against a given threat radar beam is X seconds, the test team needs to design a test procedure to test the hypothesis that the system meets the specification requirement; the null hypothesis is that the system response time is less than or equal to X seconds. The hypothesis test can have four possible outcomes as shown in Figure 1-8.

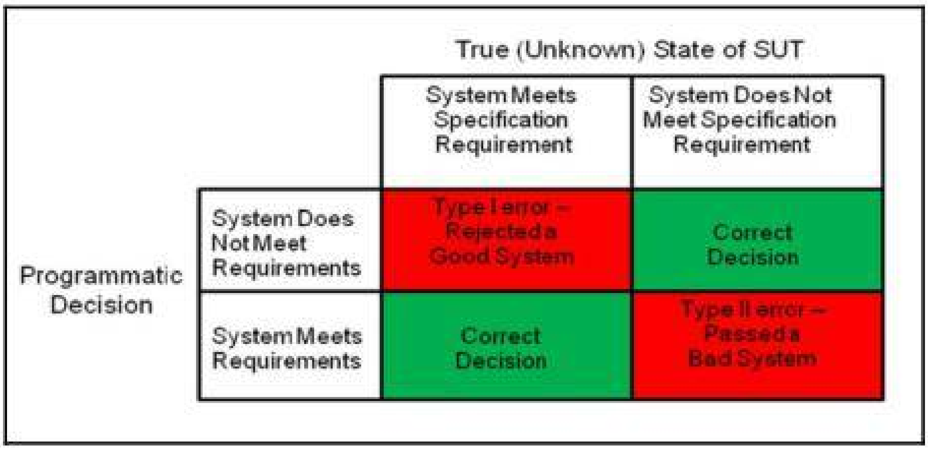

Figure 1-8: Types of Decision Error.

Basically, a Type I error occurs when a 'good' system is incorrectly rejected for failing to meet the performance specification requirement and a Type II error occurs when a 'bad' system is incorrectly accepted as having met the performance specification requirement. There are many excellent references on the statistical techniques of determining probabilities. A typical approach is to specify the probability of a Type I error (the significance level of the test) and design the test procedure such that the probability of incurring a Type II error is acceptably small (this determines the power of the test). [22] Generally, the likelihood of incurring Type I or Type II errors can be reduced by increasing the sample size. Experimental design techniques can optimise the quality of information provided for given cost and schedule constraints.

When a mismatch occurs between the objective of the test and the resources available, the test team needs to work with programme management to bring the objectives and the resources into alignment. If the programme is under-resourced and the risk of incurring Type I or Type II error is deemed to be too great, programme managers can either provide additional resources to bring the risk up to an acceptable level or they can modify the objectives. Conversely, if the risk analysis shows a low risk of incurring Type I or Type II errors, programme managers might choose to reallocate the resources to other higher risk programme elements.

1.8.3 Programme Tailoring, Phasing, and Regression Testing

The purpose of a DT&E test programme is to ensure that the SUT meets all of its critical specification and military utility requirements, and is ready to begin dedicated OT&E. The test team must construct a test programme that tailors the test objectives to the most cost-effective resources for accomplishing them. For example, if a test objective can be satisfied using a laboratory facility this will almost always be timelier and less expensive than accomplishing it in-flight on an OAR.

Testers should be aware that testing described in previous sections does not usually occur in a linear fashion. Each programme has unique requirements and related test objectives that drive where, how much, and in what order testing will occur. For example, most programmes require multiple SIL entries to check out hardware, software, and mission data changes throughout the programme.

SUT maturity is a major driver in determining which resources are needed. A new acquisition programme will likely employ multiple iterations of all types of test resources. Alternatively, a mature system with developed hardware and software being installed on a new aircraft would employ resources focusing on airframe installation effects and avionics integration. Most major acquisition programmes employ block cycle upgrades or other scheduled incremental capability deliveries. When these new capabilities are delivered the test philosophy should address two aspects: evaluating the newly delivered capability and performing regression testing to ensure that existing capabilities have not been inadvertently degraded.

Sequential testing using lower cost resources to validate performance before progressing to more expensive and less available resources is good risk management practice. If deficiencies are identified in the course of using less expensive test resources, they can be resolved before moving on to higher-cost, higher-fidelity test resources. The test strategy should always aim to find problems as early as possible in the programme using the most cost-effective resources.

Regression testing is a critical risk-mitigation component of a well-designed test programme. Regression testing is performed to ensure that when a change is made to one part of the system other performance aspects of the system have not been unintentionally degraded. Since the incremental approach is a planned activity, regression testing should be built into the schedule. Failure to properly plan for and conduct regression testing can result in lengthy and costly changes late in the programme.

1.8.4 An Integrated Test Approach

The system programme office has the overall responsibility for weapons system acquisition and ensuring that an integrated test programme occurs. There are two aspects to an integrated test approach. The first is organisational and deals with integrating the objectives of the stakeholding parties: the contractor, the government DT&E organisation, and the operational test agency. The second deals resource integration, i.e., ensuring that resources and facilities are employed in an efficient, cost-effective manner that avoids unnecessary duplication of effort. Figure 1-9 shows the resource categories and some examples of the types of activities that they support.

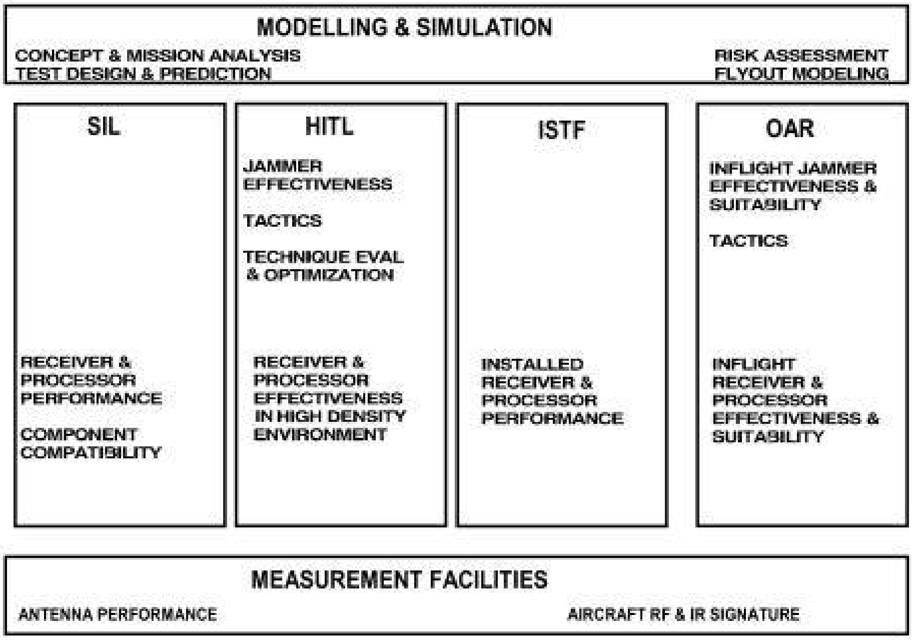

Figure 1-9: EW T&E Resource Category Examples.

The test community has a wide variety of resources available to address the established test objectives. Test managers must construct a test programme that optimises the employment of test facilities and resources to cost-effectively execute the test while maintaining technical credibility. Most test programmes will require the use of more than one facility or resource, frequently with more than one iteration. The more complex the development effort, the greater the facility or resource utilisation will be.

A typical RWR programme illustrates how a test programme should be tailored. Take the case where a new RWR is being developed for a fighter aircraft. This will involve nearly every type of resource available to the test community, starting with M&S to model antenna patterns, and detailed development testing at the contractor's facility, all the way through OAR testing.

Contrast this with the case where several years later after the RWR is fielded on the fighter platform, the same RWR is chosen to equip a transport aircraft. In this case, the RWR hardware and software are already developed. A new installation on a different platform will involve new antenna locations, and possibly new antennas. It will need to interface with a different avionics system. Also, the mission requirements of the transport aircraft will be different than the fighter aircraft and will necessitate different Mission Data Files (MDFs). Since the hardware and software are mature, the testing should focus on the risk areas specific to this programme such as installation, integration, and mission-unique attributes.

In some cases, test resources might not be available to meet the requirements of a test programme. This sometimes occurs when emerging technology outpaces the capabilities of existing test resources. In that case, the programme office might need to develop new test capabilities. Note that development and upgrading of test facilities is, in general, a lengthy process. There is a need for facility operators to identify potential future test requirements as far ahead as possible to maximise facility availability for testing.

1.8.5 Data Reduction and Analysis

The test itself only provides data, observations, and information to be subsequently evaluated. The bridge between testing and evaluation is data reduction. Often, this step is thought to be a simple act of feeding data to the computers and waiting for the output to appear on the engineer's desk. Experienced testers know differently; they are fully aware that factors such as selection of data, editing of outliers, and determination of statistical processes to be applied to the data can have a major effect on the outcome of the evaluation. A thorough understanding of experimental statistics is a prerequisite for the successful evaluation of any EW system.

1.9 EW T&E RESOURCE UTILISATION

1.9.1 Relative Cost

In general, the cost per test becomes higher as the testing moves to the right, as shown notionally in Figure 1-10. The use of models, simulations, and ground testing can reduce overall test costs since flight tests are the most costly.

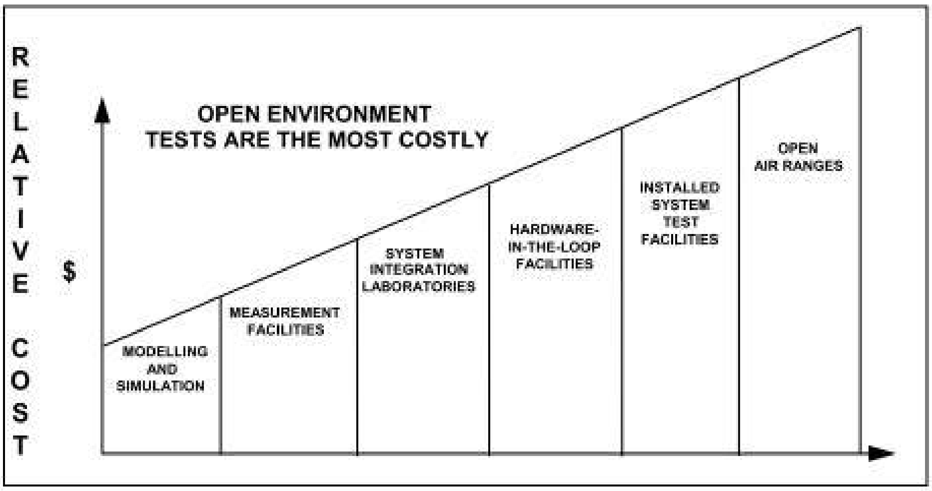

Figure 1-10: Relative Cost – T&E Resource Utilisation.

1.9.2 Relative Use

Due to the complexity of EW systems and threat interactions, modelling and simulation can be used in a wide range of progressively more rigorous ground and flight test activities. Figure 1-11, also notional, shows that M&S and MF are used throughout the test spectrum. It also shows how the number of trials/ tests should decrease as the testing proceeds through the categories.

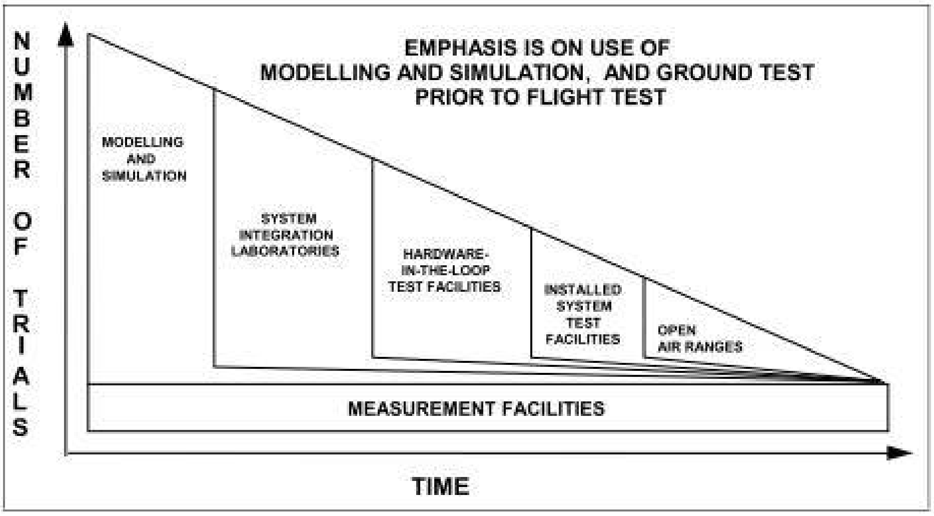

Figure 1-11: Relative Use – T&E Resource.

The key issue is to optimise cost, time, and risk of successfully gathering test evidence that allows SUT, system, and platform off contract and into operational use. To attain this two driving themes are:

- Move as much testing to the left of the development programme, i.e., from flight test to anechoic chamber ISTF and MF, and to M&S that has been subject to adequate Verification, Validation and Accreditation (VV&A).
- Only do in flight those tests that cannot be adequately achieved by ground test.

1.10 SAFETY CONSIDERATIONS

Specific safety procedures must be developed and observed for each type of test in each type of facility. The following hazards required particular attention when considering the T&E of EW systems.

1.10.1 Electrical Shock Hazards

Many EW systems utilise high-power transmitters requiring high-voltage excitation for the final output stages. In addition, nearly all EW systems make use of either 115 VAC or 28 VDC electrical power for operation. While these power sources are generally well protected when the system is installed in its operational configuration, they may be exposed and easily contacted during test activities. This is particularly true in the HITL and SIL environment.

1.10.2 Radiation Hazards

Effects of human exposure to high-intensity RF fields can vary from minor reddening of the skin to severe and permanent damage to internal organs. High power radiation can also cause equipment damage. The most common opportunity for such damage is in anechoic chambers. The Radar Absorbent Material (RAM) used in these chambers will absorb rather than reflect the RF energy from the systems in operation. The absorption of energy causes heating of the RAM. As a result, power levels must be carefully monitored and constrained to levels below that at which the heating of the RAM will result in toxic smouldering or fire. Radiation hazards can exist in all test environments but are most frequently encountered in the ISTF and OAR testing phases.

1.10.3 Pyrotechnic Hazards

EW expendables such as chaff and flares typically rely on pyrotechnic (explosive) devices for ejection. One can easily imagine the results of an inadvertent firing of these devices during ground maintenance or test operations. Also, EW pods carried on centreline or wing stations of aircraft are usually capable of being jettisoned. Unintended firing of the explosive charges that initiate the jettison sequence may result in both personnel injury and equipment damage. These pyrotechnic hazards are most likely to occur during ground test or preparation for flight test in the OAR testing phase.

1.11 THE TEST PLAN

All test activities require careful planning to be successful. Test plans come in a multitude of forms and formats, each created to ensure a specific requirement or group of requirements are satisfied in the most complete and efficient manner possible.

1.11.1 Cost and Test Budget

Adequate budgeting for each test event is critical. It is difficult to accurately predict the cost of an unplanned or poorly planned activity. Early in the programme when test events are not clearly specified, the budgeted cost for testing will likewise be only a rough estimate. The sooner more complete test planning is accomplished, the sooner the test budget can be accurately determined. Generally, as the programme progresses, the potential for acquiring additional funding is reduced. Poor budgeting at the beginning of the programme will nearly always result in cost overrun or severe constraints on test execution and failure of the test effort to deliver the required information.

1.11.2 Schedule

As with the budget, the schedule for testing is affirmed through the development of detailed test plans. Test facilities that are needed to accomplish the desired testing may have full schedules. Access to the required facilities when needed is greatly increased if detailed test planning is accomplished early and this cannot be over-emphasised.

The schedule tends to be a major driver for the budget. Inaccurate schedule projections will generally lead to budget problems and, in the end, failure of the test programme to deliver the required information.

1.11.3 Test Efficiency

Accomplishment of test events in the optimal sequence can substantially reduce the amount of retest or regression testing required. Test planning is the primary tool to understand and analyse the best sequence of events. It is also the process where experienced testers accomplish the trade studies to assess how programmatic risk will be affected by the elimination or insertion of test events.

1.11.4 The Bottom Line

It is the test planning process that permits a logical sequence of test activities with reasonable expectations at each stage. Data reduction and analysis, safety, and certainly a meaningful evaluation are all virtually useless (and probably impossible to accomplish) without a carefully developed test plan.

1.12 TRAINING – A KEY TO SUCCESS

This Handbook primarily covers the EW T&E process and its underpinning facilities, tools and techniques. It must be recognised, however, that if the staff (engineers and other) involved in these areas do not have sufficient skill and experience, then the goal of programmes with minimum cost, duration and risk will be unattainable.

The EW T&E field is a complex one, requiring high levels of specialism and experience in a number of sub-disciplines *inter alia* microwave and optical engineering, mission systems engineering, platform design and development, electromagnetics, and rig and on-aircraft T&E.

EW and T&E training is therefore of great importance if the above goal is to be met. A number of Nations and agencies run EW and EW T&E courses that can satisfy this requirement. It has been shown that such training is a great experience accelerator for novices, allowing them to function at a much higher level than would otherwise be possible. This training can also enable experienced T&E engineers to solve difficult T&E problems and make contributions to their programmes by applying detailed technical knowledge obtained from the training. [23]

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Chapter 2 – T&E OF ES SYSTEMS

2.1 INTRODUCTION

This chapter describes the basic operating principles of RF receivers, Missile Warning Systems (MWS) and Laser Warning Systems (LWS). The fundamental T&E methodologies for each type of system will be covered, beginning at the component level and progressing through fully installed system testing.

2.2 RF EW RECEIVERS

Nearly all modern RF EW systems employ some type of receiver system. Some receivers are designed for self-protection or real-time targeting; these receivers have stringent timeliness requirements and some degree of accuracy can be sacrificed to provide faster response times. Other types of receivers, such as those designed to support electronic reconnaissance and surveillance, have less stringent timeliness requirements but require greater accuracy to support their missions.

While different EW receivers serve a variety of functions, they share some common attributes. Figure 2-1 shows the basic functional architecture of most EW receiver systems:

- An aperture (usually a set of antennas to capture the RF signals of interest);
- A receiver to convert the RF signal to a video signal;
- A digitiser to convert the video signal to digital information; and
- A processor to perform the mission-specific tasks.

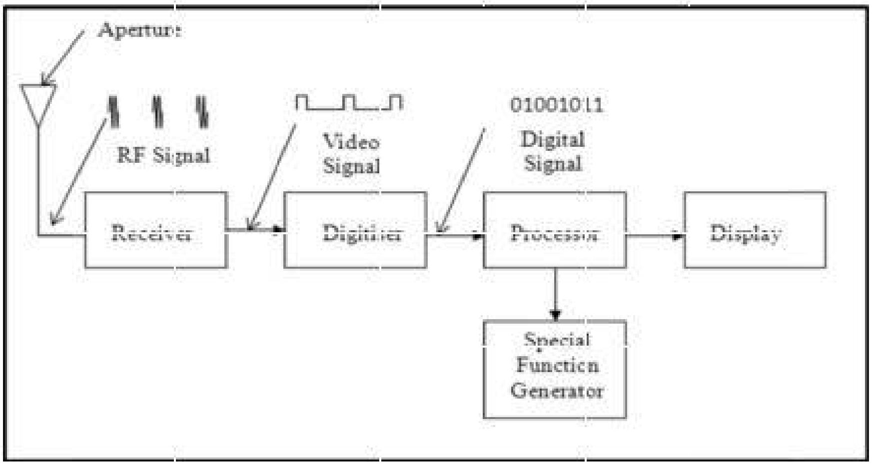

Figure 2-1: Basic EW Receiver Block Diagram.

The processor output drives aircrew interfaces such as displays and warning tones. The output is also provided to support special functions such as jammers, expendable countermeasures systems, etc. [1]

The Radar Warning Receiver (RWR) is the most widely deployed type of EW receiver system. An effective RWR performs two basic functions: to promptly warn the aircrew with sufficiently accurate information to react to a threat engagement, and to provide threat radar parametric data to other countermeasures systems, such as chaff dispensers, to optimise their performance. It is of primary importance that an RWR provide prompt indication of threat activity to the aircrew.

An electronic reconnaissance and surveillance receiver differs from warning and targeting receivers in that its primary function is data collection in support of intelligence activities, with less emphasis on real-time applications. Electronic reconnaissance and surveillance receivers also usually make high-fidelity recordings of the intercepted signals for post-mission analysis. Since their primary application is intelligence related, they typically have more stringent requirements for accurate parametric measurements. Highly accurate Angle-Of-Arrival (AOA) information is needed in cases where emitter location is necessary.

Figure 2-2 shows the main types of EW receivers: RWR, Electronic Support Measures (ESM) and ELINT. It indicates their purpose and components, and the primary differences between them. In recent times, with the significant strides made in computing power and analogue-to-digital converters, the boundary between these three types has become increasingly blurred, especially so between RWR and ESM. For the remainder of this chapter, the term 'RWR' – from an EW T&E viewpoint – is thus considered to include 'ESM'.

	RWR*	ESM*	ELINT
PURPOSE **RECEIVER COMPONENT**	**WARN AIRCREW** OF RF-GUIDED THREATS & CUE COUNTERMEASURES	**DETECT/IDENTIFY & PRECISELY LOCATE** RF-GUIDED THREATS AT LONG RANGE. ECM CUEING.	**INTERCEPTION & ANALYSIS** OF HOSTILE NON-COMMUNICATIONS EMITTERS. DETERMINE ENEMY EOB. NO ECM CUEING.
ANTENNAS (FREQUENCY SUB-BANDED)	4 SPIRALS/FREQUENCY BAND FOR AZIMUTH. 4 MORE FOR ELEVATION	INCREASED No./TYPES OF ANTENNAS, INCLUDING PHASED ARRAYS, SPINNERS	USUALLY MULTIPLE, FREQUENCY-BANDED OMNI AND DF ANTENNAS
RECEIVERS, ANALYSIS & PROCESSING	WIDEBAND & SUB-BANDED, CHANNELISED RECEIVERS. ANALYSIS SHARED WITH STAND-ALONE PROCESSOR	AS RWR + OTHER TYPES, e.g. IFM. BETTER DF TECHNIQUES. INTEGRATED PROCESSING	MULTIPLE FREQUENCY SUB-BANDED SEARCH/ACQUISITION & SET-ON/ANALYSIS RECEIVERS. INTEGRATED PROCESSING NOW COMMON
RECORDING	RARE	BECOMING COMMON	DATA ALWAYS RECORDED
DISPLAYS & CONTROLS	OFTEN STAND-ALONE	OFTEN PART OF INTEGRATED AIRCRAFT D&C	PER-RECEIVER D&C COMMON. LATEST HAVE INTEGRATED D&C

*ECM RECEIVERS HAVE RWR/ESM CAPABILITY

Figure 2-2: EW Receiver System Types.

Two other important elements of EW receiver systems are the operational flight programme (OFP) and the Mission Data Files (MDFs). The OFP is software and it functions like a computer's operating system, controlling the executive functions of the system. The MDF is analogous to a computer application; it defines how the receiver searches for and acquires signals. The MDF also contains the parametric threat definitions derived from intelligence sources, e.g., a given threat's target-tracking (TT) radar operates in a given frequency range, on a series of potential pulse repetition intervals (PRI) (or determines whether it is a Continuous Wave [CW] signal), and a scan type and/or rate (for scanning radars).

The importance of mission data in modern receiver systems cannot be overstated. In scanning receivers, such as superheterodynes, the receiver will only survey the RF environment in the manner that it is programmed. Mission data changes can fundamentally change the way that the system operates. To the tester this means that each MDF can exhibit significantly different performance and be considered as a new test item.

The management of hardware, software, and mission data also has organisational implications, see Figure 2-3. The developing and sustaining organisations are responsible for the hardware and software. The mission data is the responsibility of the military end user. In the case of a common RWR employed on both a fighter and a transport aircraft, for example, the hardware and software will be nearly identical and commonly managed, but the aircrafts' different missions will require the military end users to tailor the mission data to suit their individual requirements.

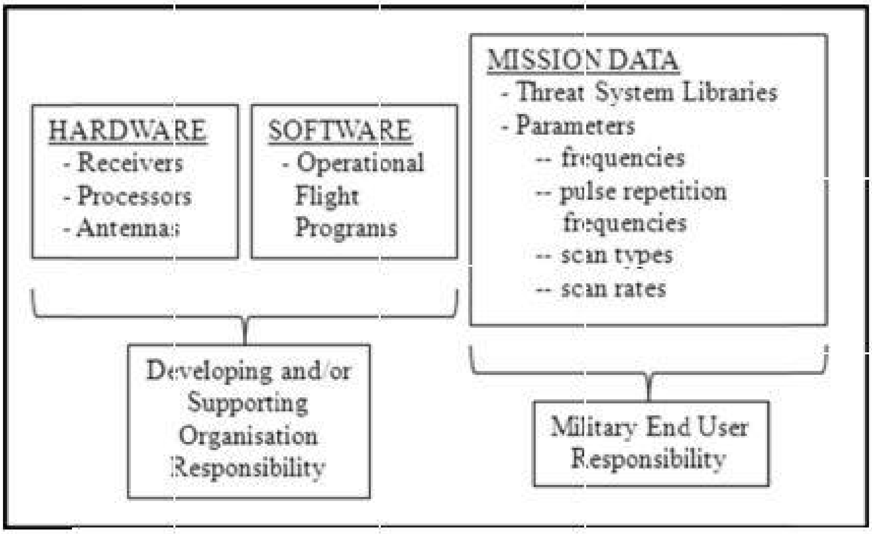

Figure 2-3: EW Receiver Elements and Organisational Responsibilities.

2.2.1 RWR System Components and Operation

The following section describes the typical components and operation of an RWR. Other EW receiver systems have similar types of components and operate in a similar manner. Figure 2-4 shows the basic layout of an integrated RWR, i.e., one that interfaces with other aircraft systems.

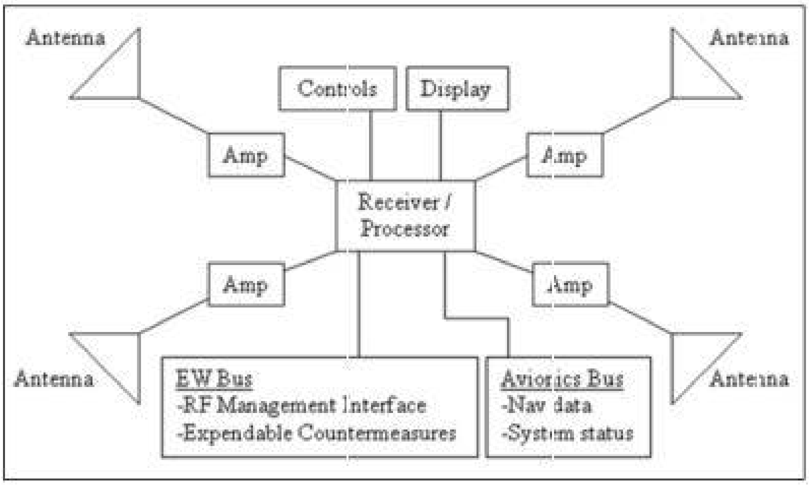

Figure 2-4: Typical Radar Warning Receiver Components.

2.2.1.1 Antennas and Transmission Lines

RWRs usually employ an array of antennas. These antennas are electromagnetic apertures tuned to the portion of the RF spectrum of interest. RWR antennas are broadband and typically cover the 2.0 – 18.0 GHz frequency range. Four orthogonally mounted antennas, each with an azimuth beam-width of approximately 90 degrees, are commonly used to cover 360 degrees in azimuth. On tactical aircraft the locations are usually at 45, 135, 225, and 315 degrees with respect to the nose of the aircraft. Elevation coverage varies, in some cases up to 360 degrees, but is typically around 30 degrees. Figure 2-5 shows a typical RWR/ESM antenna.

Figure 2-5: Typical RWR/ESM Antenna – (With permission, TECOM Industries Inc.).

The antennas generally connect to the receiver/processor in one of two ways:

- Via coaxial cable, often with an amplifier in the line to boost the analogue signal strength supplied to the receiver; and
- By employing a digital receiver located close to the antenna, which converts the analogue signal to a digital format and transmits it to the processor, thereby minimising signal power loss.

2.2.1.2 Receiver

Receivers are designed to detect specific radar signals at specified ranges and the installed receiver must have sufficient sensitivity to accomplish this task. The required sensitivity is calculated using the one-way radar range equation to determine the power density at the specified range. The installed receiver must be able to detect the signal at the calculated power density. Figure 2-6 shows a typical RF receiver transmission line and the installed sensitivity calculation.

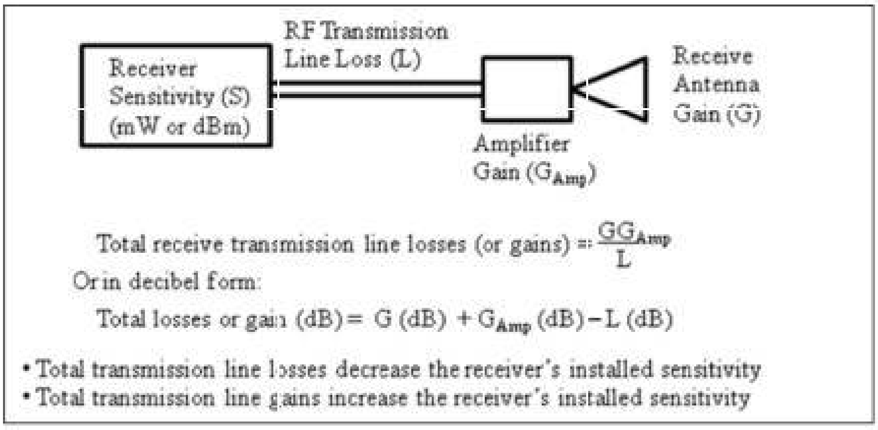

Figure 2-6: Receiver Transmission Line Components and Installed Sensitivity.

The receiver performs several functions related to signal parameter determination. The receiver creates a Pulse Descriptor Word (PDW) for each incoming pulse based on its measurements. A typical PDW is composed of information about the pulse: time of arrival based on an internal clock, AOA, signal amplitude, pulse width (or a determination that the signal is CW), and frequency.

2.2.1.3 Data Processor

The data processor takes the incoming PDWs and attempts to aggregate them into discrete pulse trains using discriminators such as AOA and frequency. Once a pulse train has been identified, additional parameters such as the PRI and radar scan type and/or rate can be measured. The PRI is merely the time between successive pulses, while the scan rate and type can be determined by analysing the time variation of pulse amplitudes. Scan rate and type information can be strong indicators of the lethality posed by the threat system.

When the individual pulse trains have been deinterleaved, they are compared to the parametric data contained in the MDF. If they match the MDF definitions, the threat beams and modes can be determined.

Further, if a threat radar system employs more than one beam, such as an acquisition radar and a TT radar, these component beams can be correlated.

Determining the AOA of a threat radar signal is an important RWR task. Amplitude comparison is a technique commonly used by RWRs to determine the AOA. The RWR typically employs four orthogonally mounted antennas arrayed azimuthally around the aircraft. The RWR samples the amplitude of an incoming signal through each antenna and can estimate the direction of the incoming signal by comparing the relative amplitudes of the four received signals.

2.2.1.4 Installation and Integration

Modern RWRs rarely operate in a standalone fashion. They commonly provide threat specific information via a data bus to other countermeasures systems such as chaff dispensers, jammers, and towed decoy systems allowing them to optimise their performance. Additionally, some functions such as emitter geolocation require the RWR to receive navigation and other information via data busses.

The information provided to the pilot indicates the type of radar that is directing energy toward the aircraft and possibly its mode of operation, its relative bearing, and an estimate of its range, together indicating its potential lethality. Many systems utilise a 3" (7.5 cm) diameter Cathode Ray Tube (CRT) to present this information to the aircrew. In newer systems the information may be presented on a page of a Multi-Function Display (MFD). The displays are oriented such that the top of the display represents the nose of the aircraft and the bottom of the display the aft of the aircraft. There may be several concentric rings on the display that are used to separate multiple threats by lethality. Many newer integrated systems display the RWR threat indications on MFDs.

The AN/ALR-56M is a widely deployed RWR. Figure 2-7 shows the system components and lists their functions. Figure 2-8 illustrates the case where a single RWR system type can be employed by more than one aircraft; in this case the F-16 and the C-130J.

Figure 2-7: RWR Components and Functions – (Courtesy of BAE Systems).

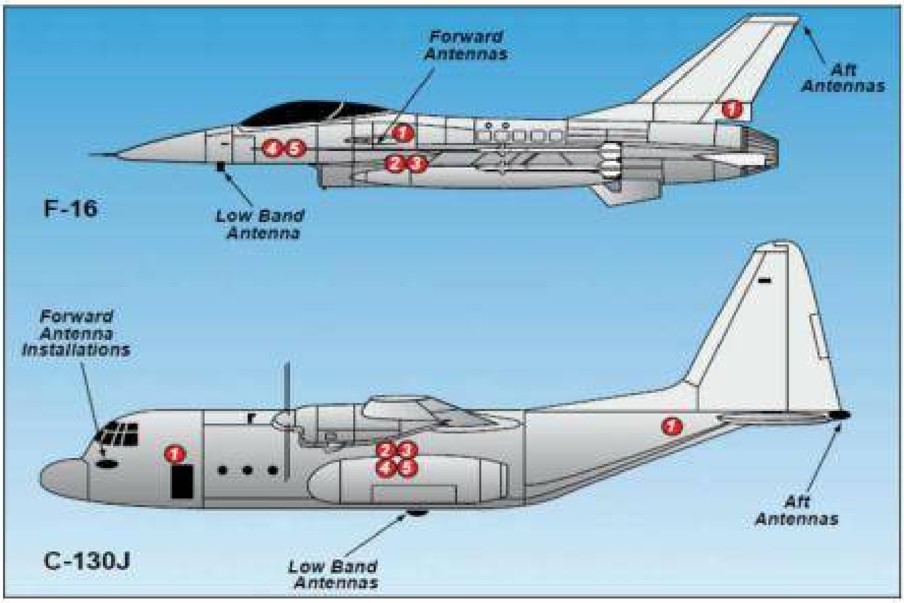

Figure 2-8: RWR Component Locations – (Courtesy of BAE Systems).

2.2.2 EW Receiver Testing (RWR Focus)

This section addresses the T&E of EW receiver systems. The following discussion focuses on RWRs but applies to other types of EW receivers.

There are many factors to consider when testing an RWR. The high-level requirements are easy to define. The system must be able to detect and identify specific radar beams, associate them with threat systems, and provide data to other countermeasures systems and the aircrew in an operationally representative environment within a specified amount of time period. These requirements are provided to the system manufacturer in a specification document.

RWR specifications and testing can be broken down into three main categories:

- DT&E of the uninstalled RWR and its constituent components;
- DT&E of the RWR as installed on the host aircraft; and
- OT&E to determine if the overall system is effective and suitable to perform its intended mission.

Each of these categories will be treated as discrete elements of testing in the following discussion. However, overlap does occur and can be very helpful in reducing programme risk. Shared participation by the following agencies' test teams allows decision makers to have access to comprehensive information throughout the programme:

- SUT manufacturer/supplier test team.
- Developmental test team, whether PSI, military or defence research agency.
- Operational (military) test team.

2.2.2.1 Uninstalled RWR Component and System-Level Testing

The RWR performance requirements can be functionally separated into testable requirements for each component. Some examples include receiver sensitivity, dynamic range, frequency selectivity, RF transmission line losses, pulse handling capacity for a receiver, and antenna gain over a field of view for a given frequency range and polarisation. These tests are normally performed by the RWR manufacturer using their laboratory test resources augmented by antenna pattern data generated from M&S sources or produced using measurement facilities. The results of these tests can also be extrapolated to estimate overall system performance.

The RWR component testing addresses design, development, and system performance. Design and development aspects are beyond the scope of this document. Individual component performance verification is important because if the individual components do not perform to their specified requirements, the overall system is unlikely to perform to its specified requirements. It is difficult to speak generically about receivers because almost every receiver is tailored to meet the specific needs of the system for which it was designed. There are, however, a few common measurements that are helpful to understand and these are described in the following sub-sections.

2.2.2.1.1 RWR Component Testing

Although comprehensive details of component-level testing are beyond the scope of this Handbook, it is helpful to be familiar with some of the measurements that characterise components. For additional information the interested reader is referred to [4]. Table 2-1 lists some commonly used receiver measurements, their definitions and their relevance to overall system performance. Other definitions are used and it is important to understand the specific meaning being used, particularly as applied to specification requirements.

Table 2-1: Common Laboratory Measurements on Receivers.

Measure	Definition	Relevance to System Performance
Minimum Discernable Signal (MDS)	The lowest power signal that can be discerned from the noise, i.e., the point where the signal power is equal to the noise power in the receiver. [2]	Receiver sensitivity directly relates to the maximum range at which a receiver system will be able to detect an emitter.
Frequency Selectivity	The ability to distinguish between signals closely separated in frequency.	The ability to process information from two emitters operating in close frequency proximity.
Dynamic Range	The input signal amplitude range that the receiver can process properly. The lower limit is the receiver sensitivity (MDS is commonly used). There is no universally accepted definition for the lower or the upper limit of the input signal level. [3]	The ability of a receiver to detect and process two simultaneous signals of different amplitudes and frequencies.
Signal Density Handling	The specified environment within which the receiver must be able to meet its other requirements for detecting and processing emitters. The number of pulses per second along with the number of CW signals is specified as well as the number and types of radars and their location (frequently specified by quadrant).	Relates to the ability of the receiver to operate in its intended environment without being unacceptably degraded.

2.2.2.1.2 Antenna Measurements

Antenna performance is a major contributor to overall receiver system performance and it is specified in two ways. The first is relative to the uninstalled configuration, which normally identifies the performance requirements for the antenna manufacturer. The second is relative to the configuration as installed on the aircraft. Generally the installed antenna pattern will be significantly different than the uninstalled pattern due to the electrical effects of the airframe. Installed antenna patterns have a significant effect on the overall system sensitivity and the AOA measurement accuracy.

Antennas are differentiated by physical size and electrical performance, in terms of gain versus frequency and gain versus AOA of the signal. Ideally, RWR antennas would be small in physical size, and have a positive constant gain over all frequencies and angles. It is possible for RWRs to cover the 2-to-18 GHz band with 3 dB (half-power) beam widths of approximately 90 degrees.

Antenna location on the aircraft can greatly influence the operation of the entire RWR. Computer modelling is used to design antennas and optimise antenna placement. Figure 2-9 shows several uninstalled RWR antennas and the left-forward quadrant antenna installed on an F-16 aircraft.

Figure 2-9: a) Uninstalled RWR Antennas – (Courtesy L3 – Randtron Antenna Systems); b) Installed F-16 RWR Antenna – (U.S. DoD Photo).

Aircraft stores, such as missiles, bombs, and fuel tanks can significantly affect the RWR antenna patterns – an effect known as obscuration. Obscuration limits the useful locations of EW antennas and is the reason why on some aircraft the RWR/ESM antennas are mounted in wing tip pods, e.g., Eurofighter Typhoon. Computing modelling of obscuration and other installed performance effects early in the design phase usually leads to optimum placement of antennas and minimum cross-coupling between antennas and their attached receivers. Such computational EM can likewise be of assistance during the T&E phase to isolate, investigate and aid resolution of any installed EW system performance issues that may arise.

LO aircraft pose a special problem for receiver and system designers. The installed antennas must have sufficient gain over the system field of view to accomplish the mission while not compromising the aircraft signature.

Due to their small size and the frequency ranges of interest, uninstalled antenna pattern measurements can usually be made in a small anechoic chamber. Figure 2-10 shows representative uninstalled azimuth antenna patterns and their variation over the 2 – 18 GHz frequency range. Installed antenna pattern measurements are commonly performed using outdoor far-field measurement facilities. Measurements are typically performed on full-scale mock-ups of either full of partial sections of the aircraft.

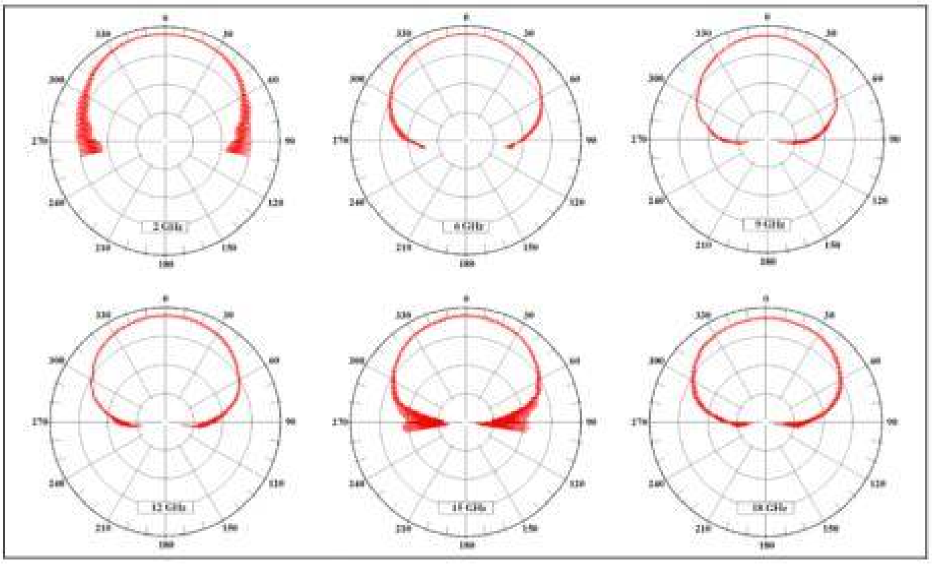

Figure 2-10: Representative Azimuth Uninstalled Antenna Gain Pattern Measurements – (Courtesy L3 – Randtron Antenna Systems).

Up front investments in antenna pattern measurements can provide significant risk mitigation. Redesigning antenna installations after unacceptable deficiencies have been identified in flight test can have serious cost and schedule consequences for acquisition programmes.

2.2.2.1.3 RWR System Level Testing

The primary purpose of RWR system-level testing is to support the manufacturer's system development and evaluation of system performance before progressing to installed system testing. System-level testing can be conducted at either the manufacturer's SIL, the PSI's Sub-System Laboratory, or at dedicated government SILs. The level of threat simulation fidelity and scenario complexity at manufacturer's laboratory facilities vary widely, from relatively low-fidelity signals and static scenarios to high-fidelity signals and dynamic scenarios.

Figure 2-11 shows a typical RWR system-level SIL configuration. At the heart of the test are the complete RWR hardware, software, and mission data. Normally, the input signals are directly injected into the receiver system and the antennas are not part of the test configuration. Additionally, most modern RWRs function as part of an integrated system on the host aircraft and interface via data buses with the other EW, avionics, and RF management systems. The RWR manufacturer typically does not have the full-up hardware and software for these systems and the data bus communications are simulated using computer-based emulators.

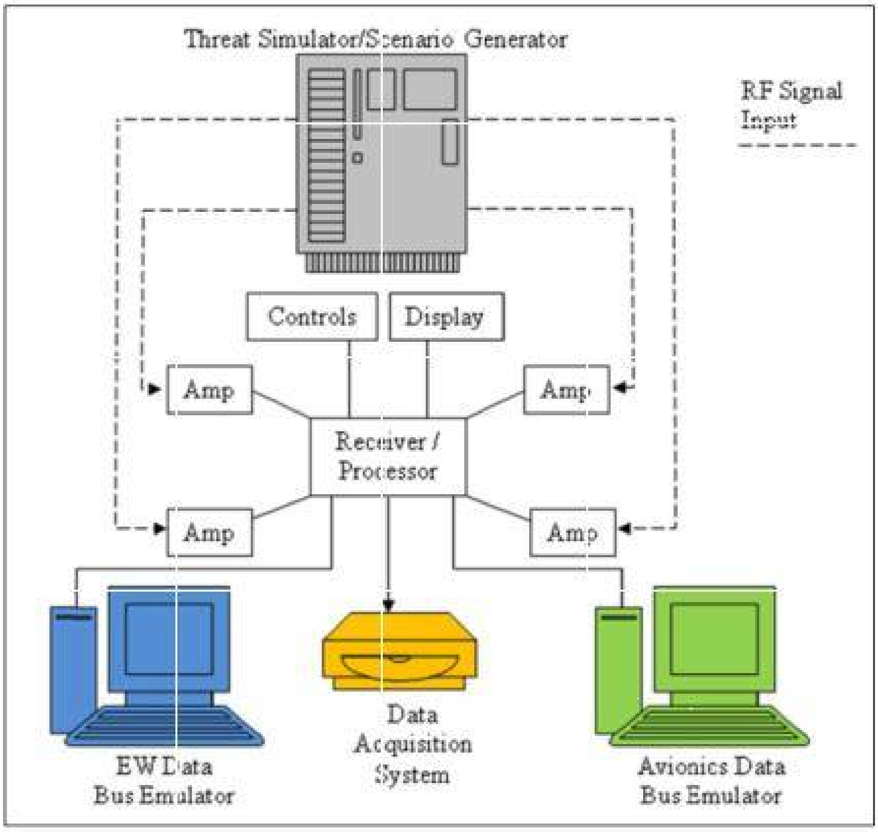

Figure 2-11: Typical RWR Manufacturer's SIL Configuration.

Complex dynamic scenarios are possible, but the RF threat simulator and scenario generator must vary the input signal amplitudes to simulate the changing threat-to-target range while accounting for the antenna effects. Antenna effects can be simulated using either modelled or measured antenna gain patterns.

System integration laboratories can be used to achieve two main objectives:

- Evaluate the performance of the uninstalled RWR system and its components; and
- Evaluate the communication between the RWR and other simulated onboard systems.

The SIL testing can evaluate the system performance against a variety of simulated threat radar systems. The specific threat systems are normally defined in the system specification and document the specific characteristics of each radar component of the threat system including: frequency ranges, PRI ranges, signal polarisation, scan types, scan rates, pulse widths, etc.

Important performance characteristics of the system can be evaluated during SIL testing allowing designers to optimise software and MDF performance. Identifying and correcting deficiencies during SIL testing allows changes to be incorporated relatively quickly, since flight certification isn't generally required.

Nearly all radars have more than one beam or mode that the RWR must detect and identify. Additionally, the RWR must perform these functions within a tactically meaningful time span. The MDF specifies the signal characteristics associated with each radar beam and mode. Initial system level testing should focus on the ability of the RWR to correctly identify each required beam and mode and the associated response times.

After the system performance has been optimised for each beam or mode and a baseline established, testing can progress to more representative scenarios. The simulated engagement scenarios model the behaviour of real individual radar directed weapons systems, e.g., a typical radar system will progress from an acquisition mode to a target tracking mode to a missile launch mode. The system should properly handle concurrent beams and mode transitions. The following paragraphs describe a typical radar directed threat engagement and the desired RWR behaviour.

A typical threat system employs a two-beam scanning acquisition radar operating on two discrete frequencies, a TT radar, and a Missile Guidance (MG) radar. Depending on how the threat is operating, one to four distinct beams may be illuminating the target aircraft. In a nominal engagement, the acquisition radar will be active and searching for targets. Once a target has been identified, the TT radar will begin transmitting and track the target. Finally, when a good track has been established the MG radar will activate to guide the missile. The MDF defines how these beams should be displayed.

The desired RWR response to this engagement is:

- The RWR should recognise that the two beams of the acquisition radar are part of the same system and should continue internally tracking both beams while correlating them and only display a single symbol representing the acquisition radar.
- When the TT radar becomes active, the RWR should internally correlate all three beams to the same system and promote the acquisition symbol to indicate that the threat status has escalated.
- Finally, when the MG beam activates the RWR should again internally track and correlate all four beams while promoting the symbol from a track indication to a missile launch indication. There should never be more than one symbol present at any time for a given threat system and it should always reflect the status of the most lethal condition associated with the identified radar beams.

The main limitations of system level SIL testing relate to the simulated antenna effects and the external data bus emulation. Most tactical RWRs determine the range to the threat radar by measuring the received power and calculating the range based on that power measurement. The installed antenna gain patterns significantly affect this measurement and even the best simulations only provide an estimate of the actual installed system ranging performance. Similarly, most tactical RWRs use a technique called amplitude comparison to determine the relative bearing to threat. The system compares the signal amplitude received by each antenna (typically by quadrant) and using this information can determine the signal's AOA. The SIL testing is very useful for developing ranging and AOA techniques, but the resulting data should be used with caution.

Since most EW T&E facilities employ direct injection of RF signals into the SUT, the antenna effects must be modelled based on the antenna-pattern data available. The injected RF energy needs to be amplitude modulated to account for antenna-gain variations over the pattern. The quality of the performance estimate is directly related to the quality of the available antenna-pattern data. Antenna data sources include: assumed-perfect patterns (smooth over the regions of interest), software-modelled patterns, or data from far-field antenna ranges. There are other AOA measurement techniques, such as phase interferometry and they present more complicated challenges to a laboratory environment. Analysts should be familiar with the limitations of AOA performance predictions based on laboratory and ground test results and use them with care.

System level integration testing is generally limited to computer-based data bus emulators which can be used to ensure that the system complies with the input and output message protocols specified in the Interface Control Documents (ICD). This level of testing rarely involves actual hardware for the data buses and other systems.

These facilities also provide an opportunity to stress the receiver system with dense signal environments to determine if the RWR can still meet its required performance specifications when the receiver and processor are heavily loaded. This test environment also allows testers to evaluate RWR performance where threat simulators or actual radar systems are not available on an OAR.

Ground testing using OAR assets can also be used to reduce risk. A receiver system can be rack-mounted and taken to an OAR where the system can get exposed to high fidelity simulators and actual radar systems. Actual radar systems have a number of peculiarities that are not necessarily captured in laboratory representations of the signals. [5] For example, a system that is considered to operate on fixed discrete frequencies may have a significant frequency shift that occurs on power up. If the RWR MDF doesn't account for this, the system might interpret the behaviour as multiple instances of the same threat system and generate multiple symbols on the display. This type of testing is a very cost-effective way to optimise the mission data prior to flight test.

2.2.2.2 Installed RWR Testing

Installed systems testing takes place with the RWR system integrated with other platform systems. There are three levels of installed system testing: the first occurs in a laboratory environment where the RWR is integrated with actual aircraft systems (this is not strictly speaking an installed system test since the SUT hardware and software are not installed on the host platform. However, it is a critical developmental activity); the second takes place during ground testing on an aircraft; and finally, flight testing is conducted using an OAR.

2.2.2.2.1 Integration Laboratory Testing

The first time an RWR sub-system will be integrated with actual aircraft hardware is normally in the aircraft contractor's or PSI's SIL facilities, also called Defensive Aids Sub-System (DASS) and Avionics Integration (AI) laboratories. These facilities, as illustrated in Figure 2-12, commonly employ mock-ups of the airframe including the cockpit and using actual hardware, cabling, and software wherever possible. In many cases, sub-systems such as the FCR are fully operational. Since previous RWR testing has been conducted with computer emulated data buses the increased level of fidelity provided by generating actual data bus traffic provides a good measure of risk reduction prior to actual on-aircraft test activity.

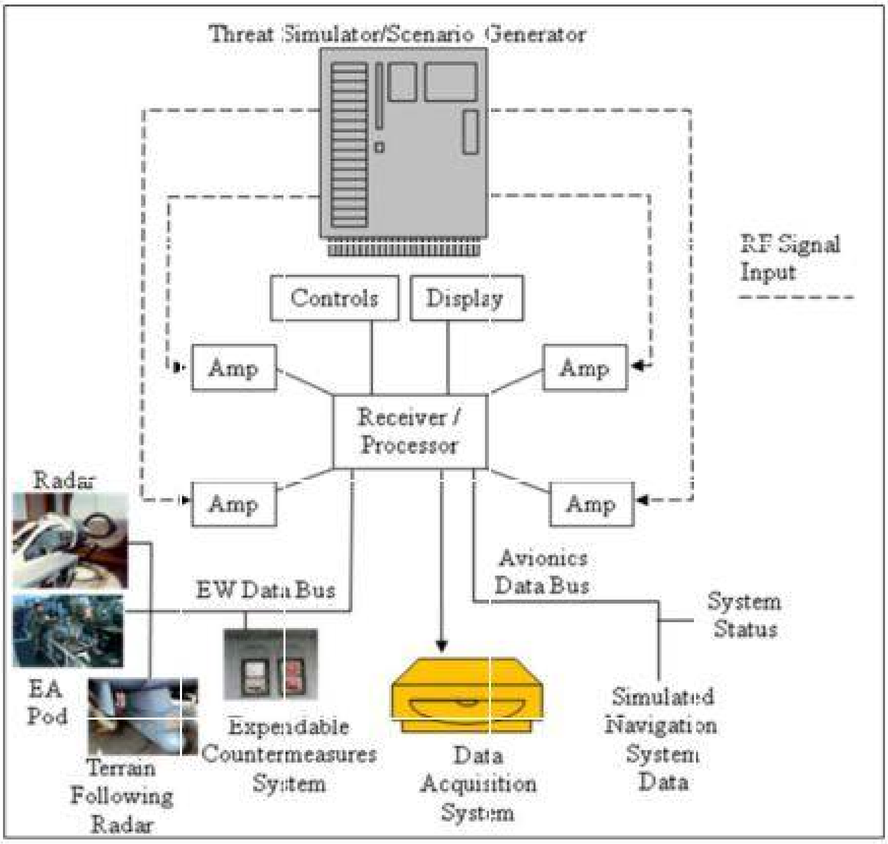

Figure 2-12: Typical Airframe Manufacturer's SIL Configuration.

The simulated RF threat signals are typically directly injected into the receiver, a technique known as 'post-antenna injection' or 'direct injection'. Testing in SIL and AI laboratories generally involves low-to-medium threat scenario densities since the emphasis is on system integration, although this can vary considerably by airframe contractor and PSI. DASS laboratory testing generally uses higher densities. Threat scenario densities used on high fidelity threat simulation equipment in these facilities can differ across Nations.

2.2.2.2.2 *Installed System Ground Testing*

Installed system ground testing can occur either in a specialised ISTF or at a convenient location on the flight line. The location of the testing is driven by the test requirements. On-aircraft ground testing allows testers the first opportunity to evaluate RWR system integration and performance on a fully equipped test article. Ideally, the test aircraft will have an RWR system installed in a production representative configuration along with all the RF transmitting systems and RF management equipment. The RF management system coordinates activity among the onboard transmitters and receivers, e.g., the fire-control radar provides information about its RF transmission to the RWR so that the RWR won't process and track it as a threat.

EMC testing is conducted to determine if the onboard RF transmitters cause EMI with the operation of onboard receivers, such as RWRs and other EW receivers, or other onboard equipment. Testing is conducted by analysing characteristics of the aircraft systems and generating a 'source – victim matrix'. This matrix identifies RF transmitters and the modes of operation most likely to interfere with the receiver systems and their operating conditions. This is typically a large matrix and a time-consuming test. Each transmitter is operated under each specified condition while the victim systems are monitored for interference. Interference can manifest itself by generating false RWR threat file tracks and/or erroneous symbols on the RWR display.

EMC testing is best conducted using an ISTF, i.e., an anechoic chamber, although if one is not available the testing can be done on the flight line. The advantage of using an anechoic chamber is the high degree of isolation from extraneous ambient RF signals. Outdoor testing in a high-ambient RF noise environment has several potential pitfalls. One is that the ambient noise will desensitise onboard receivers; another is that RF reflections from stationary objects can cause interference (such as a FCR transmission reflecting off of a hangar and causing the RWR to display a symbol) that would not occur in an anechoic chamber or in flight. Figure 2-13 shows a CV-22 aircraft undergoing testing in an anechoic chamber.

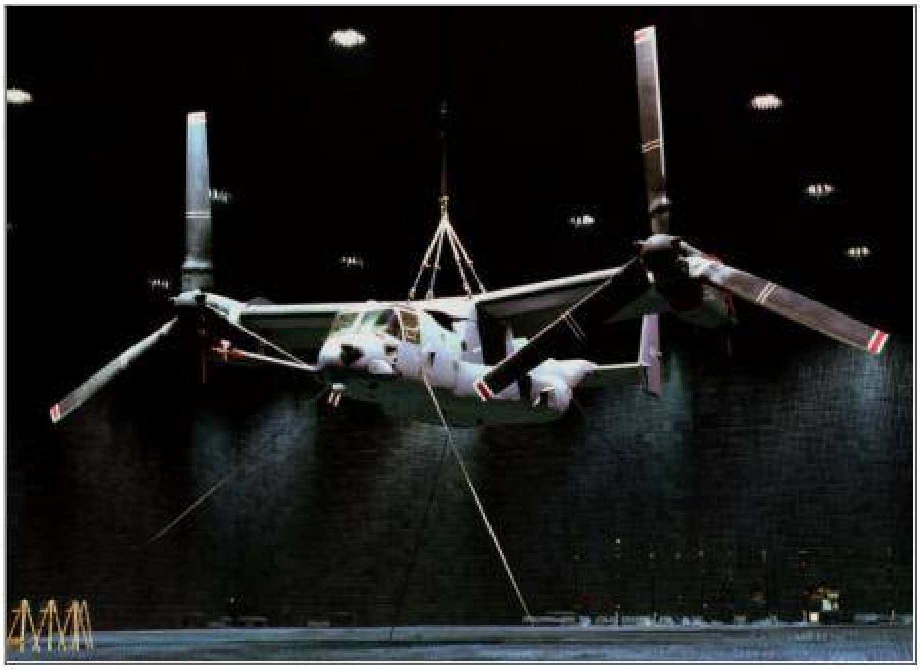

Figure 2-13: CV-22 in the Benefield Anechoic Facility, Edwards Air Force Base, California, United States – (USAF Photograph).

EMC ground testing is an excellent screening tool to reduce the number of conditions that need to be examined in flight. In most cases there will be a small number of conditions where interference is noted.

Unless there are safety of flight concerns these conditions should be repeated in flight to verify that the condition actually exists and not an artefact of the ground test configuration.

In addition to EMC testing, many anechoic chamber ISTFs have excellent threat simulation capabilities. This affords the test team the opportunity to verify the performance data from previous laboratory testing using free-space RF signals with the actual aircraft equipment and in the presence of other onboard systems operation (direct signal injection is also an option). It also represents an opportunity to fine tune mission data before proceeding to flight test.

2.2.2.2.3 Installed System Flight Testing

In one respect flight testing represents the pinnacle of realism for EW receiver testing. The SUT is operating in its intended environment with the aircraft in a flight configuration (landing gear up, engines operating, etc.), using aircraft generated power, in the presence of other operating onboard systems, and in the real-world electromagnetic environment (including civilian RF transmitters). OARs have a variety of high-fidelity simulated and actual threat radar systems providing the best available representations of those threat systems. Proper use of laboratory and ground test facilities minimises unexpected results in flight test.

The benefits and drawbacks of OARs are given in Chapter 6. The limitations of OAR testing include the limited numbers of simulators and actual radar systems, resulting in limited-signal-density environments. In addition to the cost of operating the test aircraft, the OAR range costs can be substantial. Range availability can also be an issue, particularly for lower priority programmes. These cost and schedule implications require early test management consideration. See Figure 2-14.

Figure 2-14: Flight Test Advantages and Limitations – (U.S. DoD Photo).

Another consideration involving actual radar systems is that they only represent a single instance of the combat population. If the combat population for a hypothetical radar system is assessed to operate in the 8.0 – 10.0 GHz frequency range and the single radar on the test range operates on a fixed frequency of

8.1 GHz, a large portion of the RF operating range of the radar cannot be examined at the OAR. Integrated test planning across the various test resources should ensure that those areas, particularly in terms of frequency and PRI, should be examined using ground test assets. In particular, the ground testing should cover a representative spread of threat instances to be encountered during DT&E and OT&E flight test.

Another limitation of OAR testing is that unlike the M&S, laboratory, or ISTF environments, where the RF background is totally controlled by the test planners, the OAR ambient RF environment can contain noise and nuisance signals that may affect the test. False alarms can be a significant problem and knowing the ambient signal environment can be useful in analysing unexpected behaviours of the SUT. Most OARs have excellent signal monitoring and recording capabilities to aid in this regard.

False alarm rates are normally specified for receiver systems. Usually the requirement specifies a maximum number per hour. This is a problematic measure. The false alarm rate for any receiver is integrally related to the environment in which it is operating. The limited number of flight test hours available generally makes a statistically meaningful flight test based assessment difficult (unless the performance is very poor).

The OAR provides the highest fidelity representation of the threat systems that a test programme can produce, although ground test facilities are increasingly able to generate high-fidelity threat representations. Frequently, testing will be conducted against each individual radar to establish a performance baseline for that system. Subsequent testing then focuses on the system performance in more dense multiple signal environments.

A major advantage of OAR EW receiver testing is that test aircraft are always in the far field relative to the simulated threat radar systems. This is particularly applicable when addressing MOPs that directly relate to installed antenna performance. AOA measurement error and ranging error are related MOPs.

The highest priority OAR threat simulators and radars used in support of a test programme should be those with the most relevance to the operational mission of the host aircraft. However, other less operationally relevant emitters should be considered when they allow the test team to examine how the SUT handles different portions of the frequency spectrum, polarisations, and waveforms. Airborne surrogate threat systems can also provide insight about system performance at elevation angles that otherwise could not be examined, e.g., high look-down elevation angles.

Performance estimates for MOPs such as response time, correct initial identification percentage, and correct beam correlation are generally available from ground and laboratory testing. These MOPs can be evaluated concurrently in flight using a series of profiles.

The flight test profiles describe how the aircraft will fly from a defined initial point to the end point specifying airspeeds, altitudes, and any manoeuvres. Corresponding mission and flight cards will describe how the simulated threat radar(s) will operate and how the SUT will be configured. A typical mission card will specify which radar systems will participate on the run, when they will be active and how they will operate their constituent radars (acquisition, TT, and MG) in terms of modes, frequencies, PRIs, etc. The aircrew will also have a flight card identifying the SUT configuration in terms of MDF and modes. The flight card should also inform the aircrew of the expected behaviour of the system in terms of which symbols should appear and where they should appear.

The flight profiles for an RWR test will typically begin at about twice the maximum engagement range of the radar and fly through the heart of the engagement envelope of the threat system. Throughout the run the radar will cycle through a series of scripted mode changes. Sometimes several profiles will be used to evaluate performance at different aspects and ranges. Data collected concurrently on these runs can be used to evaluate key MOPs such as response time, initial correct identification percentage, correct beam correlation percentage, and AOA error. Ranging error can also be evaluated concurrently.

Human factors considerations are also important. The symbology should be clear and should transition smoothly on the display in a manner that accurately represents the threat activity. Audible tones and cues should be clear and sufficiently loud to alert the crew.

2.2.2.3 Operational Test and Evaluation

OT&E focuses on the ability of the military end user to effectively employ the weapon system under realistic combat conditions. It also evaluates the operational suitability of the weapon system. Reliability, maintainability, and supportability are among the most important aspects of a fielded RF receiver system and these are primarily evaluated during OT&E.

One of the most important suitability considerations for a fielded receiver system is mission data reprogramming. The military end user must be able to receive and review intelligence data to determine if a mission data change is required, such as when a threat system is found to be operating on a previously unknown frequency. A very important aspect of an operational suitability evaluation is the ability of the military end user to make necessary mission data changes, rapidly distribute them to operational units in forward locations, and install them on the aircraft.

2.3 MISSILE WARNING SYSTEMS

All missile types pose a threat to military air platforms. In particular, passively-guided, IR-directed missile systems pose a major threat. The most common of these are Man Portable Air Defence Systems (MANPADS). They have accounted for the majority of aircraft combat losses over the last 30 years. Detecting missile launches, warning aircrew of this threat and cueing countermeasure employment is one of the most challenging tasks facing the ES community. Missile Warning Systems (MWS) are designed to detect these missile launches and, in the case of the MWS sub-categories Missile Approach Warners (MAW) and Missile Launch and Approach Warners (MLAW), their approach. The wide proliferation of lethal, relatively inexpensive, man-portable threat systems and the increased level of terrorist activity in recent years have led toward equipping ever more military aircraft with MWS.

2.3.1 MWS Technologies

There are three types of MWS technology:

- Active RF – Pulsed Doppler (RF-PD), e.g., ALQ-156;
- IR, e.g., DDM-Prime; and
- UV, e.g., AAR-54(V).

There is no single technology that is yet fully adequate for all aircraft roles, missions, scenarios and operational theatres. The main benefits and drawbacks of each technology is summarised in Table 2-2.

Table 2-2: Summary Comparison of MWS Technologies.

MWS Type	ADVANTAGES	DISADVANTAGES
RF-PD	• Measures distance and speed of approaching missile, enabling accurate Time To Impact (TTI), and thus aiding optimum countermeasure employment. • Tracks the missile all the way to impact. • Not as sensitive to weather conditions as IR and UV MWS.	• Limited range compared to IR and UV MWS due to practical levels of RF and prime power, cooling, volume and cost constraints. • 'Beaconing' effect can allow MWS RF transmissions to be detected and utilised by threat weapon targeting systems, especially those using modern 'digital' receivers. • Cannot measure DOA accurately, so cannot cue DIRCM systems or optimise flare/chaff dispensing on basis of DOA. • Potentially vulnerable to hostile jamming and mutual interference from formation flyers, although radar ECCM and synchronisation techniques are effective. • Small, low RCS missiles could lead to late detection and countermeasure cueing. • Generally higher mass, volume and prime power than IR and UV MWS. • Integration more difficult than passive MWS due to need for RF interoperability with other on-board emitters and receivers.
IR	• Longer detection range than RF-PD and, at altitude (where there is little ground clutter) than UV MWS. • Good DOA for DIRCM cueing, presuming enough sensors. • Generally lower mass, volume, prime power than RF-PD MWS. • Passive system, so no EMCON issues. • Relatively easy installation and integration compared to RF-PD MWS. • Dual-band ("two-colour") IR MWS give improved performance.	• Relatively high FAR compared to RF-PD and UV MWS. Needs extensive 'false threat signal database' and complex processing to cater for large natural (solar) and man-made IR clutter. • Generally higher mass, volume and prime power than UV MWS. • IR sensors require cryogenic cooling, adding to mass, volume, prime power and cost when compared to UV MWS. • TTI is algorithmically calculated, rather than measured as in the RF-PD case, leading to sub-optimal cueing of time-critical countermeasures.
UV	• Greatest benefit at low operational altitudes for use against short range SAMs launched from modest ranges. • Longer detection range than RF-PD MWS. • Better FAR performance than IR MWS, especially in the Solar Blind UV region, where there is little clutter. • Good DOA for DIRCM cueing, presuming enough sensors. • Generally lowest mass, volume and prime power of the three technologies. • Passive system, so no EMCON issues. • Relatively easy installation and integration compared to RF-PD and IR MWS.	• Cannot detect a burnt-out, i.e., coasting, missile. • Modest detection range compared to IR MWS. • Cannot provide range but can derive TTI from rapid increase in amplitude of approaching missile's signal.

Around the time of Issue 1 of this Handbook, there were about the same number of RF-PD and passive (IR/UV) MWS either in service or under development. At that time, IR and UV systems suffered from much higher False Alarm Rates (FAR) than RF-PD systems. In recent times technology developments have led to the trend in MWS toward IR/UV technology, for a variety of reasons including FAR improvements, cooling and power requirements, EMCON and cost. RF-PD technology, however, being radar-based, continues to provide the most accurate missile speed, Time To Impact (TTI) and Range to Impact, which are necessary to optimise the timing of flare/chaff and other countermeasures appropriate to the engaging missile type. Set against this is the IR- and UV-based systems' superior detection range.

The technically optimum MWS would likely be a combined RF and IR/UV system, with the latter passively cueing the active RF RF-PD system in order to minimise EMCON hazards. Generally, such a solution is, in effect, the same as fitting two MWS to an aircraft. This poses significant power, volume, mass and installation constraints, especially on fighter-sized aircraft, and is also often unaffordable.

Given the increasing predominance of IR and UV MWS across NATO Nations, the remainder of Section 2.3 concentrates on passive MWS. Many EW T&E aspects covered therein are equally applicable to any of the three MWS technology types. Key differences concern the method of stimulating a RF-PD MWS when compared to passive MWS testing:

- RF target generators, similar to those used for FCR testing, are used during SIL/HITL/ISTF T&E.
- Flight testing of MWS performance can include:
  - Missiles fired captive on rocket sleds, with overflying aircraft carrying the RF-PD MWS.
  - Firing artillery shells in a carefully controlled trajectory to appropriately approach an overflying aircraft's trajectory so as to trigger missile warning declarations by the MWS.

2.3.2 MWS Components and Operation

Passive-threat warning systems are designed to detect the EM radiation from the rocket motor of the threat missile. Detection can occur due to the rocket motor ignition (launch detection) or by detection of the burning motor and body heating effects during fly-out (in-flight detection). Most modern systems employ sensors that use a combination of the two types of detection. Figure 2-15 shows a simplified MWS block diagram.

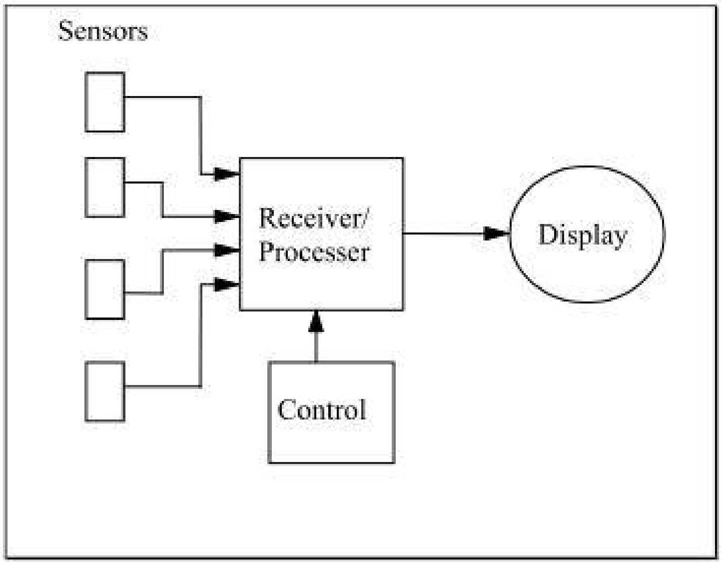

Figure 2-15: Simplified MWS Block Diagram.

MWS face the classic probability of detection versus probability of false alarm trade off. The MWS detectors must be sensitive enough to rapidly and reliably detect the missile's EM signatures and provide either the aircrew or, if in automatic mode, the Defensive Aids Suite's (DAS) countermeasures element sufficient time to react and cue an effective countermeasures response. The system must, at the same time, distinguish an actual missile launch signature from the extremely cluttered electromagnetic background. A false alarm occurs when background radiation produces an alarm in the MWS without the presence of a missile launch.

Modern MWS employ several techniques to minimise false alarms. These techniques fall in into three basic categories and can be used in combination:

- **Spectral** – Analyses specific portions of the EM spectrum to ensure the detection is consistent with the spectral signature of an actual rocket motor.
- **Temporal** – Examines the signal amplitude of a detection over time. As a missile closes in on a target, the range between the missile and the target will decrease while the signal amplitude received by the detector should increase exponentially.
- **Kinematic** – Compares the expected spatial behaviour of a missile on an intercept path with the spatial behaviour of a detection. A missile on a collision course with a target will have very small angular movement in the inertial reference frame (as opposed to the aircraft body axis reference frame).

2.3.2.1 Sensor

Passive MWS fall into two broad sensor categories: scanning and staring. IR passive warning systems were first developed over 30 years ago. Present day systems can use either scanning or staring sensors. These systems normally operate in the mid-IR (4 to 5 micrometers wavelength) or the UV bands. Scanning systems provide high-resolution direction-of-arrival information that can optimise countermeasures employment.

However, they generally give up some processing capability because the relatively long scan period can prevent the MWS from detecting the signature characteristics needed to identify the threat. Staring systems continuously cover large fields of view (up to 90 degrees) continuously. This can reduce sensitivity because the system is monitoring a larger area.

The UV portion of the electromagnetic spectrum features lower background noise than the IR region, with good signatures from missile rocket motors. These sensors are typically low-cost, simple photo-multiplier devices that are very rugged. They are typically staring, wide field-of-view (90 degrees or more) sensors. Figure 2-16 shows the uninstalled MWS components and a typical sensor installation.

Figure 2-16: Top: AN/AAR-54 Electronic Unit and Sensors – (Courtesy of Northrop Grumman Corp.); Bottom: Aft Missile Warning Sensor Installation on a C-130 – (USAF Photo).

2.3.2.2 Processor

Threat detection algorithms are usually based upon a number of criteria. Signal-to-noise ratio is a fundamental parameter. The MWS looks for a signal that exceeds the background signal level from the environment, for signal stability and possibly a particular signal amplitude growth which is characteristic of an approaching threat. It may also look for other time-dependent characteristics such as an ignition pulse followed by a short time delay before main motor ignition, typical of shoulder-launched SAMs.

MWS algorithms must differentiate between a complex battlefield EM environment and an approaching missile. It must also correctly distinguish a missile that is targeting the host aircraft from one that is approaching but not targeting it, i.e., one launched at another aircraft. These are very subtle distinctions.

2.3.2.3 Display

A standalone MWS will have a very simple display providing audio and visual information. The audio information consists of tones to alert the pilot to a new threat and the visual information will be some estimate of the Direction Of Arrival (DOA) of the approaching threat, usually only with quadrant resolution. An integrated MWS will most commonly use the MFD or Head Up Display (HUD) to provide the pilot with missile warning information. However, the displayed information may not be any more sophisticated than a few simple tones and quadrant DOA information.

2.3.3 MWS Testing

MWS testing parallels RF receiver testing in many respects, but differs in some important ones. The primary difference between RF receiver testing and MWS testing is that RF receivers are designed to detect and process active manmade signals associated with a weapon system, while missile warning systems are designed to detect the EM signature of a rocket motor and discriminate the signature from the background EM environment.

The MWS system-level performance testing requires exciting the SUT with a signal that will produce a threat indication. There are three common methods:

- Stimulators;
- Missile plume simulators; and
- Actual rocket motors.

Stimulators are the lowest fidelity means of exciting a system. They do not necessarily represent a missile launch signature, but have sufficiently representative EM signature characteristics to produce a response from the MWS. Different MWS employ different false alarm rejection methods and testers must be aware of them to ensure that the stimulator is not rejected by the MWS (at least in a way that will compromise the test objective). Static stimulators require the test aircraft to fly very constrained profiles to avoid triggering the kinematic false alarm rejection logic. Stimulators are very useful for system flight line checkouts and integration testing where high-fidelity simulation is not required.

Missile plume simulators provide a high-fidelity temporal and spectral representation of a missile launch. The Joint Mobile Infrared Countermeasures Test System (JMITS) shown in Figure 2-17 is an example of a system incorporating IR and UV missile plume simulations.

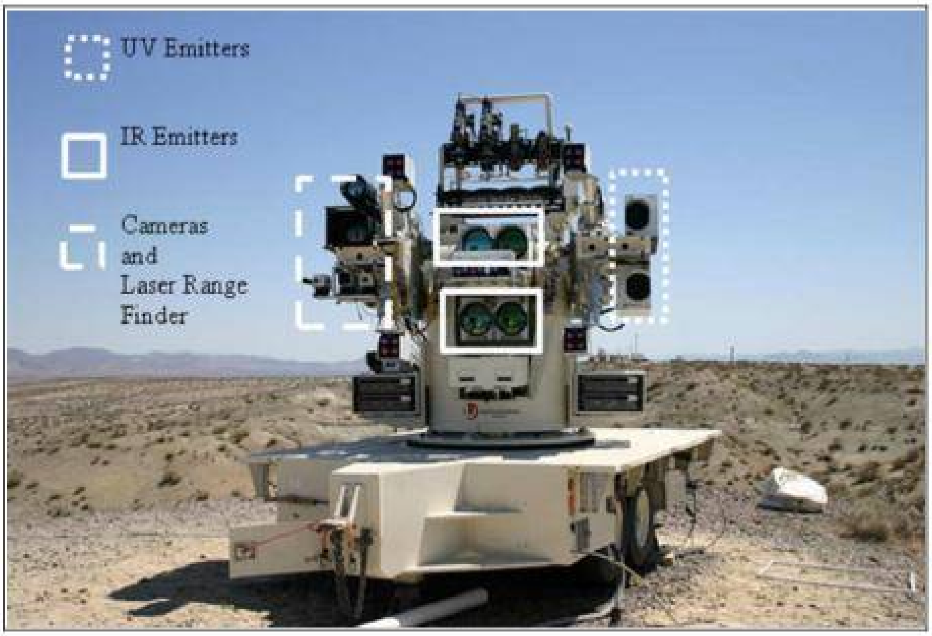

Figure 2-17: Joint Mobile Infrared Countermeasures Test System – (U.S. DoD Photograph).

There are several methods of simulating dynamic behaviour. One involves a string of pyrotechnic devices or lamps with the appropriate spectral characteristics. Each device is sequentially activated along the string. This sequential activation produces an apparent motion simulating a missile launch and fly out. If the test aircraft flies an appropriate flight path, the geometry will approach that of an intercept course. Dynamic missile plume simulators are under development. These systems will be towed by a support aircraft and provide high-fidelity temporal and spectral representations with the added capability of realistic kinematics.

Actual missile firings can either be performed using captive missiles on a sled track or live fires. The captive missile launches using a sled track is a similar approach to "string of lamps". The test aircraft can fly low over the captive missile launch and simulate an intercept geometry. Live missile fire testing, where remotely piloted vehicles or other unmanned platforms are used to carry the MWS, tests the system in as close to a tactical environment as possible.

2.3.3.1 Uninstalled MWS Testing

Uninstalled MWS DT&E allows system developers to evaluate system level performance without requiring installation on or integration with the host platform. Testing in this context includes use of cable cars and flying test beds, where the MWS hardware is present but not usually in an aircraft configuration.

2.3.3.1.1 MWS Component Testing

The manufacturer tests individual MWS hardware and software components during system development, such as uninstalled sensor field-of-view and detector sensitivity. The processor algorithm optimisation process begins with SIL testing where sensor output data from actual flight testing are recorded and injected into the processor. This allows for repeated tests against a wide variety of backgrounds and atmospheric conditions without actually flying.

2.3.3.1.2 *MWS System-Level Testing*

System-level testing focuses on MWS ability to distinguish missile launch signatures from background clutter and generate a timely alarm. It can be conducted in SILs, on flying test beds, or on cable cars. A major consideration in MWS development is collecting background environment data to optimise detection and false alarm rejection algorithms. Background testing is conducted using either a flying test bed or the intended host platform to collect environmental background data using the MWS sensors. When false alarms occur, the test team will try to identify the sources and collect as much data as possible for analysis. On false alarm analysis completion the manufacturer will modify algorithms to eliminate or at least minimise the number of false alarms. A database of responses is maintained for future analysis.

Cable car testing is a special case of ground testing where the SUT is exposed to actual missile launches in a dynamic environment. An instrumented MWS is installed on a cable car with a heat source that an IR-guided missile can track. The heat source is commonly suspended some distance below the cable car to reduce the chance of the missile impacting it and the MWS. The cable car is then pulled across a valley, presenting the missile with a realistic target. When the desired test conditions are achieved, a gunner, posted a specified distance down the valley, fires a missile and the MWS response is recorded. Figure 2-18 illustrates the concept. The primary benefit of this type of testing is that an actual missile launch and fly out satisfies the spectral, temporal, and kinematic requirements for a valid declaration.

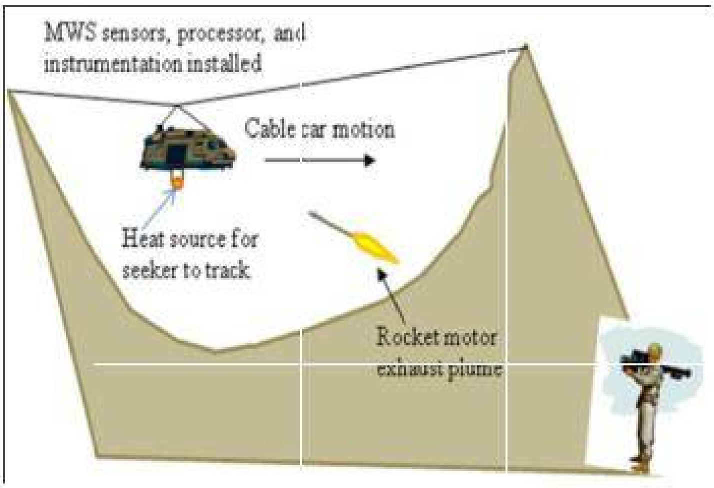

Figure 2-18: Cable Car Test Setup.

2.3.3.2 Installed MWS Testing

Much of the required MWS development and testing can be accomplished without having the MWS installed on a production representative aircraft. The final phase of MWS testing should focus on its integration with other aircraft systems and platform-specific installation characteristics, such as field of view.

Ground testing using stimulators to actuate the MWS can be used to ensure that the system has been properly installed and integrated with other aircraft systems. This type of testing is a good way to identify and correct system design deficiencies before flight testing.

Ultimately, the DT&E programme should produce results that characterise the installed MWS performance. This evaluation should focus on system's ability to detect and declare threats, warning time, false alarm susceptibility, and flare dud detection. Mobile missile plume simulators provide a valuable tool for evaluating the MWS performance in a variety of background and atmospheric conditions. This testing is often accomplished as part of an end-to-end test with countermeasures systems such as flare dispensers and directed IR countermeasures systems (arc lamp- or laser-based).

The proliferation of MANPADS and the threat they pose to modern aircraft has driven an increased demand for MWS installations on ever more platforms. Commonly, a MWS that has been developed and fielded on one platform will be chosen as the MWS for a new platform, thereby reducing development costs. T&E efforts of this nature should then focus on integration with multiple aircraft systems and provide detailed platform-specific installation characteristics.

As with other systems, reliability and maintainability are determined using statistical data acquired over time. Re-programmability is the capability of changing parameters or algorithms in the system to meet new threat scenarios, while minimising the costs of upgrading or replacing hardware.

2.4 LASER WARNING SYSTEMS (LWS)

Airborne laser warning systems are currently provided mainly for low and slow aircraft, including helicopters, although some are also being fitted to fast jet aircraft. The primary threat systems of interest are AAA systems employing a laser range finder and laser beam-riding missiles.

2.4.1 LWS Components and Operation

An LWS is functionally similar to the MWS shown in Figure 2-15. In general, LWS consist of sensors to detect the laser signal, a processor to analyse the data, and a mechanism to warn the pilot. Laser detectors are commonly integrated with the sensor modules of MWS and often share a common processor. Typically, 6 – 8 sensors are required to provide spherical coverage. Figure 2-19 shows a typical LWS.

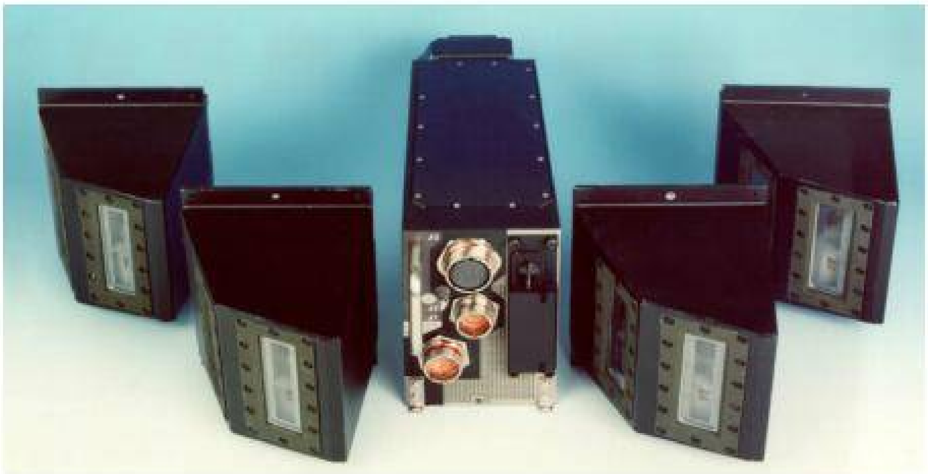

Figure 2-19: 1223 Laser Warning Receiver System – (Courtesy of SELEX GALILEO).

2.4.1.1 Sensors and Receivers

Sensor designers must consider several characteristics unique to lasers. Lasers generally operate either on a fixed wavelength or are tuneable over a relatively small wavelength range. The particular operating wavelength is determined by the lasing material. Additionally, laser beams are coherent light sources with very little beam divergence, unlike radar. When a laser is illuminating the target aircraft, the laser beam may or may not directly illuminate the sensor aperture and the sensor must be able to detect the laser energy scattering off of the airframe or through the atmosphere. Detecting atmospheric laser scatter in the presence of intense background clutter presents a significant challenge.

2.4.1.2 Processor

False alarm discrimination, while still an important consideration, is less challenging to LWS than to MWS. Laser beams are man-made phenomena and are unlikely to be mistaken for anything else. A laser beam illuminating an aircraft in a combat environment is a strong indicator of hostile intent.

2.4.1.3 Display

Laser warning displays are commonly integrated with MWS displays or other integrated threat displays. The displayed information is similar in structure to MWS symbology.

2.4.2 LWS Testing

Many of the same concepts discussed in the MWS testing section apply to lasers as well. LWS testing requires stimulating the laser sensor with a signal of sufficient fidelity to trigger a system response. The level of fidelity is driven by the test requirement. In the most basic case, flight line integration testing and system checkouts can be accomplished with a laser operating on a suitable wavelength. In other tests, the pulsed structure associated with a beam-riding missile may be required.

2.4.2.1 Uninstalled LWS Testing

The uninstalled testing is similar in concept to MWS testing.

2.4.2.1.1 LWS Component Testing

Laboratory testing measures several critical parameters. The sensitivity of the sensor at various operationally relevant wavelengths directly relates to the maximum range at which a threat system can be detected. Off-axis sensitivity is also a key consideration for laser warning sensors because they must be able to detect energy scattered through the atmosphere and/or off the airframe. Dynamic range is also an important consideration because the sensor must detect the very low energy levels associated with atmospheric scattering as well as the direct illumination of the aperture by the laser beam. Since receiver sensitivity is degraded when operated in bright sunlight, sensitivity is also measured in outdoor tests; however, the measurements obtained in this manner are not as accurate as laboratory measurements because atmospheric scintillation can cause fluctuations in the received power density.

2.4.2.1.2 LWS Level Testing

Flight tests are conducted to determine if there are problems unique to the flight environment. Significant testing can be accomplished without having the system installed on a production aircraft. Flight tests on a flying test bed are particularly useful in evaluating the maximum detection range and false alarm susceptibility in an operational environment. Maximum detection range is determined in airborne tests by flying the aircraft both towards and away from the threat, and noting where detection is obtained or lost.

2.4.2.2 Installed LWS Testing

Flight tests must be conducted to verify that neither the installation nor integration with other avionics has significantly altered system performance. Of particular note to installed system testing are compatibility with other aircraft systems, EMI, field-of-view restrictions, scattering of laser radiation from aircraft surfaces, and aircrew operational interface. Airborne tests are also conducted to ensure that the receiver can perform in an aircraft environment (vibration, temperature, pressure and EMI/EMC). Atmospheric scintillation can affect the AOA accuracy, and aircraft parts can affect the field of view. Even for quadrant detection systems, it is important to determine how the receiver handles the transitional regions between quadrants.

The laser beam rider missile is an increasing threat to aircraft. Beam rider detection presents a special challenge because of the extremely low irradiance levels involved. A beam rider simulator should be provided for ground and airborne tests; one that can produce not only the proper wavelength, but also the proper pulse coding because detection algorithms used to get good sensitivity can be affected by the pulse code format.

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Chapter 3 – T&E OF EA SYSTEMS

3.1 INTRODUCTION

This chapter addresses the T&E of the following types of EA systems:

- RF Self-Protection Jammers, RF Support Jammers and RF Towed Decoys;
- Active Infrared Countermeasures Systems and Countermeasures Dispensing Systems;
- Low Observable Systems; and
- Directed Energy Systems.

Figure 3-1 shows a sampling of EA systems.

Figure 3-1: Electronic Attack System Examples – (US DoD Photos, except the ALE-55 Towed Decoy, which is Courtesy of BAE Systems).

Each section addresses the general function, concepts of operation, and components of the subject EA system. The T&E of each type of system is also addressed at the component, sub-system, and integrated system levels. System level testing is approached from two aspects: uninstalled and installed. Uninstalled testing refers to all system and sub-system testing that is not conducted on the intended host platform. Installed system testing is that accomplished with the system installed on the intended host air vehicle.

3.2 RF SELF-PROTECTION JAMMER

SPJ are defensive EA systems that protect their host platform from hostile radar directed weapons systems. These systems can either be installed internally within the airframe or carried externally in a pod.

3.2.1 Radar Operation and Jamming Types

Understanding how radar systems work in light of the countermeasures that will be employed against them is important. The two categories of radar systems that will be discussed are TT radars supporting weapon direction and search or surveillance radars. Semi-active missile seekers are special cases of TT radars. Radar systems supporting weapon direction require very accurate target state information (azimuth angle, elevation angle, and range and/or radial velocity).

Radars can be classified as one of three types: Low Pulse Repletion Frequency (LPRF), Medium PRF (MPRF), and High PRF (HPRF) radars – including CW radars for the purpose of this discussion. LPRF radars track targets in angle (azimuth and elevation) and range. MPRF radars track targets in angle, range, and radial velocity. HPRF and CW radars track targets in angle and radial velocity. Some HPRF and CW radars also employ sophisticated techniques to measure target range. Table 3-1 summarises the characteristics of each radar type.

Table 3-1: Radar Types and Performance Characteristics.

Radar Type	Range Performance	Doppler Performance	Comments
LPRF	Unambiguous	Ambiguous	Generally cannot achieve good unambiguous Doppler performance
MPRF	Ambiguous	Ambiguous	Can achieve good unambiguous range and Doppler performance but requires the use of sophisticated waveforms and processing
HPRF, including CW	Ambiguous	Unambiguous	Can achieve good unambiguous range performance but requires the use of sophisticated waveforms and processing

The following discussions focus on LPRF and HPRF radars. Countermeasures directed at tracking radars aim to disrupt their TT capabilities by corrupting their target state information, thereby degrading or denying weapon employment.

A conventional low PRF radar system transmits a pulse of energy and measures the time that the pulse takes to make the round trip from the radar to the target and back. Since the radar pulse is travelling at the speed of light, the range to the target can be determined, but it is important to remember that the fundamental measurement is time-based. Similarly, pulse Doppler and CW radars measure the Doppler-shifted frequency of the signal returning from the target relative the transmitted frequency. This shifted frequency can be calibrated to the radial velocity of the target, but it is crucial to remember that the radar isn't measuring radial velocity, it is actually measuring frequency. Consequently, countermeasures directed at conventional pulsed radars create range errors by corrupting the time-based measurements of the radar. Similarly, countermeasures directed at pulse Doppler radars create radial velocity errors by corrupting the frequency measurements of the radar.

Radars can also be classified as coherent or non-coherent types. The coherent ones can measure Doppler with good accuracy but they need a constant fingerprint (RF and PRF) during the integration interval (a few milli-seconds) and can, due to that, be more sensitive to jamming.

Angle tracking is the most important of the tracking domains for TT radars associated with weapons systems. Many types of weapons systems can prosecute a successful target engagement in the presence of large range or velocity errors. Essentially, this is because the radar is still providing a line of sight to the target to the fire control system. Even relatively small angle tracking errors can sufficiently degrade the weapon system's performance to prevent a successful engagement. The most effective jamming result against a TT radar is to create an angle tracking error sufficiently large that the system breaks lock on the target. A break lock requires the threat system to re-acquire the target and re-initiate the weapon employment process.

TT radars employ two basic types of angle tracking mechanisms: Amplitude Modulation (AM) and monopulse. The AM techniques, such as sequential lobing, Track While Scan (TWS), and Conical Scan (CONSCAN) are mostly used by older radar systems. These techniques employ a scanning radar beam or series of beams to sequentially sample the target amplitude returns. When the boresight of a beam is pointed at the target the radar will receive the largest amplitude return, and when the boresight moves away from the target the amplitude will drop off. These amplitude variations can be used to produce an error signal and drive an automatic angle tracker. Monopulse angle-tracking radars instantaneously produce amplitude (or phase) errors in the azimuth and elevation channels, as opposed to the AM trackers which do it sequentially. Nearly all modern radars employ monopulse angle trackers and they have a high degree of immunity to AM angle jamming.

Radio frequency defensive EA systems employ active RF jamming transmissions to disrupt the operation of hostile radar systems. These transmissions can be broadly classified as either:

- **Noise Jamming** – Noise jamming attempts to increase the noise power level in the victim radar's receiver thereby decreasing the signal-to-noise ratio and correspondingly its maximum detection range. Figure 3-2 shows several types of noise jamming. Barrage noise spreads the jamming energy over a relatively wide frequency range. This technique has the advantage of covering a large frequency range and does not require any knowledge about the victim radars but at the cost of diluting the jamming power. Spot noise transmits the jamming energy over narrow frequency ranges and can achieve high power levels but requires knowledge of the victim radar's operating frequency. Swept spot noise sweeps a relatively high power signal through a frequency band of interest. This allows high jamming power levels and does not require knowledge of the victim radar, but at the cost of leaving the victim radar un-jammed some portion of the time.
- **Deceptive (or Deception) Jamming** – Deceptive jamming, also known as false target jamming, presents the radar with target-like waveforms with the intent of deceiving either an operator or the automatic detection and tracking features of the radar.

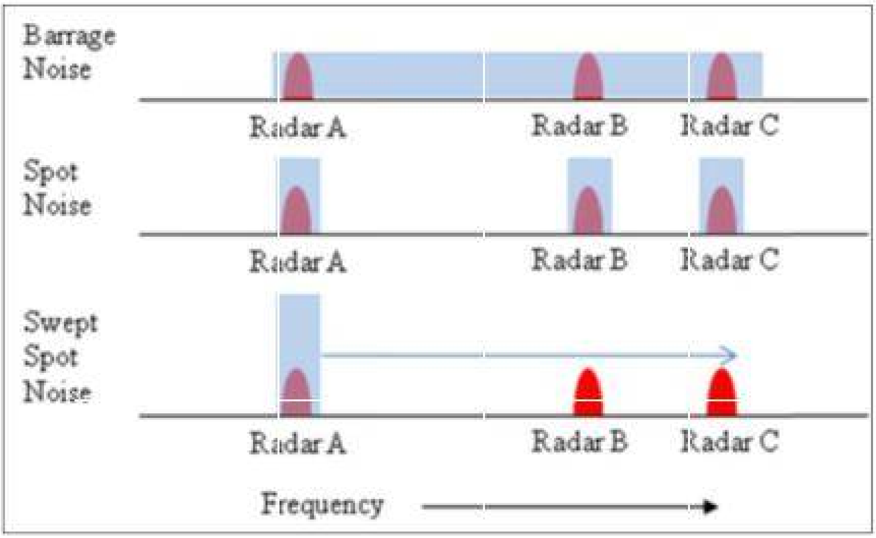


Figure 3-2: Types of Noise Jamming.

3.2.2 RFCM System Concepts and Operation

An RFCM system has several basic components. The front end of the system is similar to an RWR and consists of an antenna or an array of antennas, RF transmission lines, and a receiver/processor. In addition to the front end of the system, the RFCM system has a technique generator, a modulator/transmitter module used to modulate and amplify the jamming waveform and the transmit RF transmission lines and antennas. Figure 3-3 is a simplified block diagram of a RFCM system.

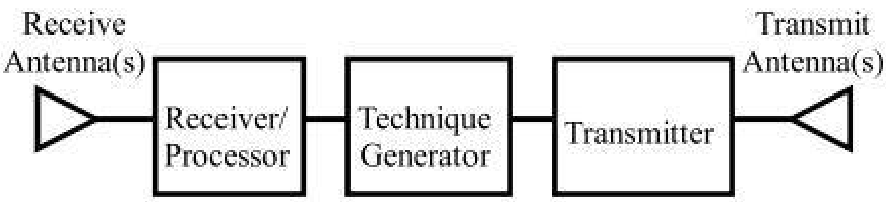


Figure 3-3: Simplified Jammer Block Diagram.

Figure 3-4 shows the individual components of the Advanced Integrated Defensive EW Suite (AIDEWS). AIDEWS is an example of a typical modern self protection jammer; this particular system also performs as an RWR and a controller for other onboard EW systems.

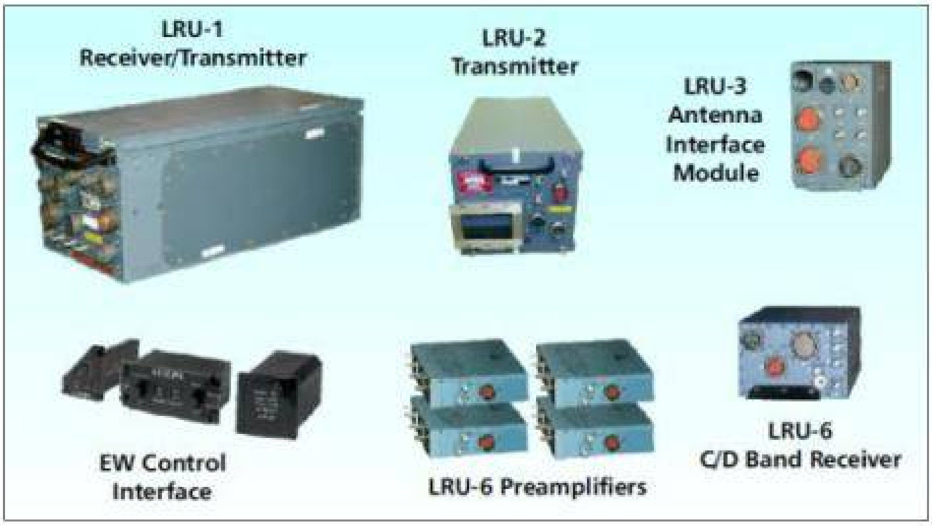


Figure 3-4: Typical Self-Protection Jammer Components – (Courtesy of ITT Corporation).

3.2.2.1 RF Front End and Receiver/Processor

The front end of an RFCM system is very similar to an RWR. It must survey the RF environment and, based on its mission data programming, identify, determine the angle of arrival, and prioritise incoming threat signals. All of the discussion in Section 2.2 about receivers applies to RFCM receivers as well.

3.2.2.2 Technique Generator and Transmitter

When the processor has identified and prioritised the threat systems in the environment the system will then determine a countermeasures response. The MDF identifies the optimum technique or series of techniques that will be transmitted against the threat system. Most RFCM techniques attack the victim radar's tracking domains: range, Doppler, and angle and the MDF contain the parametric definitions of these techniques.

The technique generator may use oscillators, or a part of the incoming signal, and time, frequency, and/or amplitude to modulate the signal to achieve the desired technique. The transmitter then amplifies and transmits the jamming waveform.

Modern radars employ a variety of EP techniques to improve their signal processing gain and mitigate the effects of hostile EA. Many of the EP features employed by modern radars address the ability to discriminate between the radars' transmitted waveforms and jamming waveforms. Therefore, it is becoming more critical in deceptive (false target) jamming that the jamming waveforms resemble the radar waveforms such that they are not rejected by the victim radar's EP logic. Digital RF Memory (DRFM) technology is increasingly being employed in RF countermeasures systems. DRFM-based techniques allow a jammer to produce very high quality false targets. They do this by sampling the incoming pulses and storing them. The stored pulses retain the nuances of the received pulses, such as phase coherency or intrapulse modulation. These stored pulses can them be modulated and re-transmitted back toward the victim radar.

3.2.2.3 Transmit Antennas

The RFCM system designers employ a wide variety of transmit antenna configurations. Regardless of the transmit antenna configuration it is designed to direct as much jamming energy as possible back toward the threat system. The system may have dedicated transmit antennas or it may timeshare an RF transmission line with the receive system. Dedicated transmit antennas can be as simple as just forward and aft antennas or may be as complicated as multiple electronically steered phased array antennas.

3.2.2.4 Displays and Controls

The aircrew interface usually consists of a control panel for selection of system operating modes and indicator lights identifying the threat environment. Typical operational modes for the jammer consist of standby, receive only, and transmit. Some displays will show which threat systems are being countered.

3.2.2.5 RF Management Systems

SPJ systems transmit high power RF energy that can adversely affect SPJ operation as well as that of other onboard systems. Antenna isolation is an important consideration for EMC. Ideally, the receive antennas on an aircraft would be electrically isolated from the transmit antennas and the receiver would not detect any onboard-generated RF transmissions. However, if there is insufficient isolation to prevent onboard receivers from detecting and processing the transmitted signals, their performance can be affected.

Potential inference examples include the SPJ system detecting, processing, and jamming the fire control radar; the RWR seeing the SPJ system transmissions, misinterpreting them and erroneously displaying threat symbols; the SPJ receiver seeing the SPJ system transmissions and processing them as threats (a condition known as ring around). System designers attempt to optimise antenna placement to meet the system's field of view requirements and to maximise isolation.

An RF management system, such as a blanker, must be employed where insufficient antenna isolation exists to prevent the receiver from seeing the transmitted signals. Installed system testing allows testers to determine if the chosen RF management scheme has been properly implemented. Temporal blankers merely 'turn off' the target receiver when the related transmitter transmits and verifying the correct timing of the blanking pulses is critical. More sophisticated schemes pass operating information from the transmitting system such as frequency and PRF, so that the receiver can identify the transmitted signal and then ignore it.

3.2.3 SPJ System Testing

The discussion from Section 2.2 on RWR testing applies to the receiver aspects of SPJ systems. In addition to the receiver components, the SPJ system has additional components and considerations related to the transmitter portion. There is a significant difference between testing an RWR and testing an SPJ system. The RWR is an open-loop system. It merely monitors the environment and communicates information to the aircrew or countermeasures systems. The SPJ is a closed-loop system, as is the radar system it is attacking. While it surveys the environment in the same manner as an RWR, its purpose is to actively disrupt the behaviour of the threat system.

If the SPJ system is effective, it will cause the threat system and/or its operators to adapt to the jamming and likewise the SPJ system will respond to changes in the threat-system behaviour. This dynamic environment greatly complicates the T&E of SPJ systems. It is imperative that the test team, including the test planners and the analysts, have a thorough understanding of not only how the SPJ system operates, but also how each of the victim radars works and how they are employed operationally.

Two measures that are central to SPJ system T&E are miss distance and Jamming-to-Signal ratio (J/S). These measures are important indicators of overall system performance. Unfortunately, both are difficult to measure directly and can be difficult to interpret. These measures must be considered throughout the development programme and should be re-evaluated as higher fidelity measurement data becomes available.

SPJ effectiveness is evaluated by its ability to improve the survivability of the host aircraft. This ultimately involves determining the success or failure of an engagement by a hostile weapons system. The success or failure of an engagement is determined by the miss distance of the missile or the bullets in the case of a ballistic system. The degree of survivability improvement afforded by the SPJ can be inferred by statistically comparing the miss distance data collected under the same conditions with the SPJ off versus the miss distance data with the SPJ operating, conditions known as 'dry' and 'wet', respectively.

Since the evaluation involves a weapon miss distance, it can only be performed through M&S or live-fire testing with unmanned aircraft. Live-fire testing provides very useful anecdotal information about the SPJ system effectiveness and performance but, due to the cost, rarely produces enough data to make statistically relevant performance estimates about the population. Operationally, the SPJ system is only one contributor to aircraft survivability. Other contributors include chaff, manoeuvres, and tactics. Since all of these are interrelated it is extremely difficult to cost effectively isolate the specific contribution of the jammer to aircraft survivability.

The relationship between the SPJ system output and its effectiveness is complicated and somewhat counter-intuitive. The J/S ratio is the SPJ system jamming power entering the radar's receiver divided by the target skin return signal power entering the radar's receiver. The J/S ratio is an important measure and it is vital to understand its implications.

The jammer power entering the victim radar's receiver increases as the jammer gets closer to the victim radar. Although it would seem to, this does not result in increased jammer effectiveness, because while the jammer power is increasing, the target skin return signal power is also increasing, but at a much faster rate. Annex C discusses this in more detail. Thus, with all else being equal, the jammer will become less effective as the range to the victim radar decreases. At some point the jamming will become ineffective. The range at which this occurs is called the burn-through range.

An SPJ system can be functionally decomposed and the performance of each component can be determined and evaluated. Key performance measures are good indicators of SPJ system performance. As the performance of each component is better understood, the assumptions underlying the M&S can be refined and the fidelity of the M&S improved. In-depth analysis can take the overall effectiveness requirements and determine how the various components of a given design must perform in order to achieve them. The decomposed requirements identify important performance specifications for system components such as installed system sensitivity and Effective Radiated Power (ERP). The EMC of all RF transmitters and receivers in their installed configurations must be characterised. The EMC test results allow designers to eliminate or mitigate EMI effects.

As with RWRs, SPJ system specifications, testing, and performance assessments can be broken down into three main categories: T&E done on the SPJ system and its constituent components, T&E done on the SPJ system as installed on the host aircraft, and OT&E to determine if the overall system is effective and suitable to perform its intended mission. The SPJ system testing has additional requirements related to the transmitter and related components. The system also requires evaluations that focus on the behaviour of the operators of the victim systems.

3.2.3.1 Uninstalled SPJ Component Testing and Performance Assessments

Uninstalled SPJ testing can be either open or closed loop. Open loop testing is conducted by injecting the SPJ's receiver with simulated RF threat signal(s), to stimulate the processor and transmitters, and monitoring the output jamming waveform. The SPJ output does not affect the input signal and the effectiveness of the jamming waveforms cannot be evaluated. Closed loop testing includes a representation of TT radar receiver, TT loop, and radar operator, and allows effectiveness to be evaluated.

3.2.3.1.1 Open Loop Component and System Level Testing

Testing performed at the manufacturer's laboratory facilities is almost always open loop and focuses on individual components' performance and, at the system level, ensuring that SPJ output is consistent with expectations based on the RF input. Receiver and processor component testing is addressed in Section 2.2.

The technique generator should, based on the processor's identification and the received RF threat signal, select and generate the countermeasures technique defined in the MDF. The specific RF output of the technique should be measured to ensure that the frequency, timing, amplitude, and pulse characteristics are consistent with the intended technique. The timing relationship between the input RF signal input and the jamming output signal is critical, especially for false target generators. Additionally, when more than one radar-directed threat system engages the host platform, it is necessary to verify that the system properly prioritises the associated threat signals and correctly assigns the transmitter resources. It is important to ensure that the most lethal threats receive jamming resource priority.

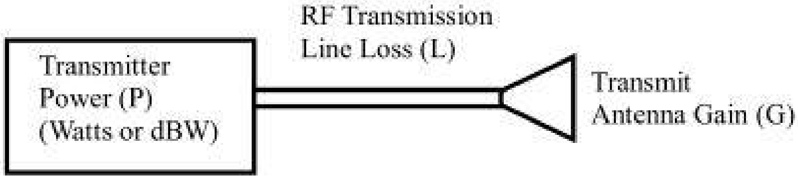
The SPJ J/S ratio spatial coverage should be evaluated on a threat-by-threat and technique-by-technique basis. This allows analysts to determine where the jammer will and will not be effective. While J/S cannot be directly measured in a laboratory, a complete analysis can be performed based on laboratory measurements, modelling results, and other measured characteristics. The J/S is a function of range to the target and these other factors:

- Threat radar system ERP;
- RCS of the SPJ host aircraft; and
- SPJ system ERP.

The threat system ERP is the power directed by the threat radar toward the aircraft carrying the SPJ. It is a function of the radar transmitter power, transmission line loses, and transmit antenna gain. Threat system ERP is commonly obtained from intelligence estimates.

The RCS of the aircraft carrying the SPJ system can be obtained either from software-based predictions or measured at an RCS measurement facility.

The SPJ power directed toward the victim radar is the product of the transmitter output power, the RF transmission line loss, and the transmit antenna gain. Figure 3-5 shows the components of an SPJ transmit path and how ERP is calculated. The transmitter power output can be measured in the laboratory. Transmission line losses can be estimated from waveguide and RF switch characteristics of the system design or measured on the aircraft, if available. Installed antenna gain patterns can either be obtained from either software-based predictions or measured at an antenna pattern measurement facility.



$$\text{Effective Radiated Power (ERP in Watts)} = \frac{P\,G}{L}$$

Or in decibel form:

$$\text{ERP (dBW)} = \text{P (dBW)} - \text{L (dB)} + \text{G (dB)}$$

Figure 3-5: RF Transmit Path Components and Effective Radiated Power.

The RF spectrum of the transmitter should be characterised in the laboratory. An ideal transmitter only amplifies and outputs the specific signal injected into it. However, real transmitters often produce 'extra' or **spurious signals**. Spurious signals are most likely to occur at harmonics of the injected signal but they may appear anywhere in the spectrum due to limitations and/or errors in system design, manufacture, or installation. These spurious signals waste valuable jammer power and in some cases can be exploited by a threat system's EP features.

3.2.3.1.2 Closed Loop System Level Testing

HITL test facilities generally present the first opportunity to examine the closed-loop SPJ system performance and effectiveness. HITL simulations typically employ high-fidelity threat simulations and sometimes generate realistic simulated displays to support a threat operator in the loop. The simulation also generally employs a scripted aircraft flight path and a dynamic engagement geometry that accounts for the changing RCS and transmit and receive antenna gains, and can be used to generate a realistic J/S ratio throughout the simulated engagement. The operator in the loop is a critical element of the threat system's EP design. The HITL testing can be used to optimise the SPJ technique design to deceive the man in the loop.

Since HITL simulations incorporate high fidelity threat simulations they can support detailed SPJ performance and effectiveness evaluations. The measures associated with the tracking loops of the radar such as range and/or radial velocity error and azimuth and elevation angle errors can be generated from dry and wet cases and compared to evaluate performance. Simulated missile and projectile fly-out data can also be generated and the dry and wet cases can be compared to evaluate the system effectiveness.

There are a variety of threat system models with varying degrees of fidelity that address threat system behaviour, especially the radar, fire control system, and missile or projectile aerodynamics. Analysts need to understand what the various threat models do and how they work, particularly with respect to how the operator is addressed.

The HITL testing is a cost effective way to generate significant amounts of data. Limitations include a scripted flight path (i.e., the aircraft doesn't normally react to the engagement, it just flies a predetermined path and the SPJ system is normally operating in a standalone configuration without the effects of other onboard systems). The HITL also provides the best chance to evaluate system performance when a simulated or actual radar system is not available on an OAR.

Another case of system-level closed-loop testing occurs when an SPJ system is rack-mounted, normally in a trailer, and taken to an OAR. The system can then be tested against OAR radar threat simulators to evaluate closed-loop performance. This type of testing is often called pole testing because the receive antenna is mounted on a pole and elevated some distance above the ground to mitigate the effects of multi-path and reflections. This type of testing has the advantage of working against a simulated or actual tracking threat radar systems. Limitations include the static configuration and the lack of actual RCS or antenna pattern effects.

3.2.3.2 Installed SPJ Testing and Performance Assessments

Installed-system ground testing is primarily open loop and focuses on aircraft system integration and EMC testing. Integration testing can either occur at the PSI's SILs or on the aircraft. Increasingly, ISTFs are capable of generating high fidelity threat simulations and limited closed loop capabilities.

3.2.3.2.1 Installed-System SPJ Ground Testing

The PSI will conduct integration testing in their SILs to ensure that the SPJ system properly communicates with other onboard systems. The SPJ manufacturer, as is the case with the RWR manufacturer, normally will emulate data bus traffic. The PSI's SIL will often be the first time that the SPJ will interface with other actual aircraft hardware.

The EMC testing discussed in Section 2.2.2.2.2 also applies to SPJ systems. Additionally, an ISTF can cost-effectively expose the SPJ to high fidelity threat representations such that the end-to-end performance of the installed SPJ can be evaluated in a secure environment. Occasionally, EA technique deficiencies are discovered and can be corrected before moving on to flight testing.

Some ISTFs have developed limited closed loop test capabilities. The test team needs to ensure that the test objectives are tailored to be compatible with the limitations of these capabilities.

3.2.3.2.2 Installed-System SPJ Flight Testing

Flight testing presents the ultimate 1-versus-1 (1-v-1) closed-loop environment to evaluate the SPJ system performance. The SPJ is normally in a production-representative configuration and all of the testing takes place in the far field (testing will sometimes be conducted in various non-production configurations to support specific development test objectives). The system operates against a high-fidelity simulated threat radar or actual radar system with operators in the loop. The operator is a key EP feature of many threat systems. A well-trained operator can recognise jamming techniques and manually intervene to counter the effects of the jamming and maintain radar track. Operator skill is an important consideration in any SPJ system testing.

Rules Of Engagement (ROE) define operator behaviour during the test, particularly with respect to the EP features the operator is allowed to use. Two of the most common ROE address optical systems and reacquisition procedures. Operators are frequently precluded from using optical systems to aid tracking (a good optical angle track can be used to provide angle information to the tracker in lieu of radar angle track information). This is often done to simulate night conditions. When the jammer is effective and causes the victim radar to break lock, the operator needs to know how he will go about reengaging the target aircraft. This brings up a case where the test team needs to balance test efficiency with realism. The fastest way to reacquire the target is to allow the operator to use the OAR's real-time instrumentation truth data to locate the aircraft. This approach maximises the amount of data collected during limited-range times. The most realistic method is requiring the operator to use the onboard acquisition radar system. The test team must weigh the value of additional data versus the more realistic conditions. The ROE for a given threat system and SPJ system will vary with the specific test objectives. The importance of clearly defined ROE cannot be overstated and the entire test team should be involved in their development.

The performance of an SPJ system can be degraded by the operation of other onboard transmitters, e.g., the blanker may inhibit jammer transmissions when the terrain-following radar is transmitting (the TF radar will generally have priority). Comparing the 1-v-1 performance under similar conditions of the jammer when it is operating alone to its performance in an operationally representative condition (with other onboard systems operating) allows analysts to determine if the RF management system is degrading the SPJ system performance. Multiple-ship operations also need to be considered. For example, the interactions of jammers and fire-control radars within a tactical fighter formation need to be examined to determine potential limitations.

In-flight J/S measurement can be a valuable tool but generally requires specialised, non-operationally representative EA techniques to be loaded in the SPJ systems MDF. One technique, shown in Figure 3-6 delays the EA response from the incident radar pulse by a fixed time period. The separate returns are collected in discrete range gates. Since there are an infinite number of points around the aircraft the test team needs to carefully select the flight test profiles to ensure that data are collected at the required frequencies, aspects, and ranges.

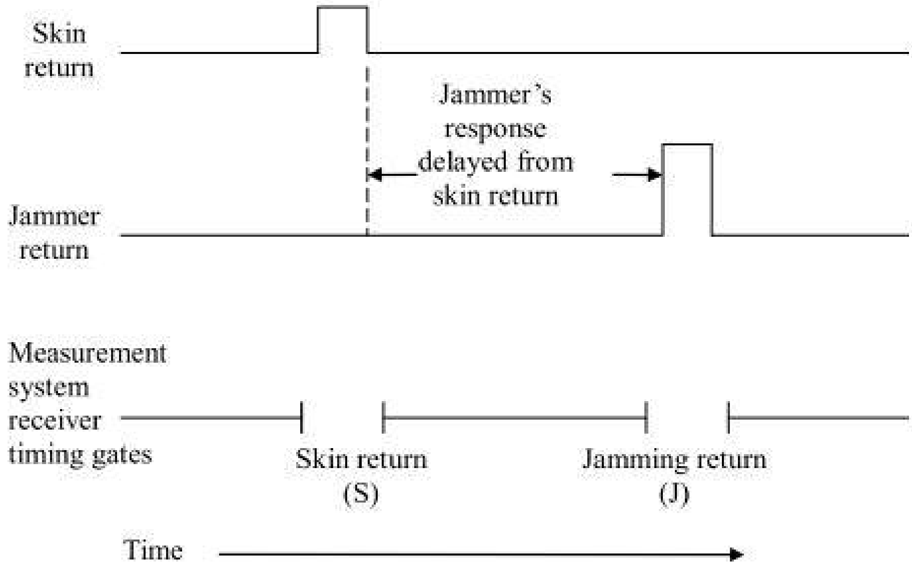


Figure 3-6: Example J/S Measurement Technique.

There are a number of limitations associated with flight testing on an OAR. As is the case with RWRs, only a small number of threat simulator systems exist on an OAR. If a required threat system isn't available on an OAR, the best level of fidelity that can be achieved is using a HITL facility. The background environment is limited and thus restricts the pulse densities that can be achieved to evaluate the SPJ performance at required high-pulse densities.

EMC testing on some airborne SPJ systems can only be accomplished in flight. This type of testing may or may not require OAR ground-based radar participation. If the test aircraft has sufficient onboard ability to stimulate and control the SPJ system to achieve the desired test conditions, OAR support may not be necessary.

3.2.3.3 Additional SPJ T&E Considerations

Many decision makers want to quantify the contribution that an SPJ makes to aircraft survivability and ultimately mission accomplishment. It is difficult to isolate the jammer's contribution because there are a number of interrelated complementary factors that affect survivability and the jammer's effect is only one of these.

Another consideration working against the direct applicability of DT&E flight test results to operational effectiveness assessments is that operational aircrews do everything possible to minimise their exposure to hostile air defences. An aircraft when detected and engaged by a hostile air defence system will, to the extent possible, practice threat avoidance, e.g., terrain masking, employ other countermeasures such as chaff, and employ tactical manoeuvres in concert with the active jamming. If DT&E were conducted according to this philosophy, the test team might not get much data and the data collected would confound the jammer effects with other factors.

A developmental tester wants to collect as much relevant data as possible about the SUT. Due to the cost of OAR time and scheduling difficulties, this often drives the use of non-operationally representative test profiles (ones that maximise the exposure to the threat systems to make the best use of valuable range time) that isolate jammer performance so that it can be segregated from other factors. It is important to remember that even though this type of testing isolates the jammer performance, it does not necessarily translate into quantifying the jammer performance for operational effectiveness assessments.

In most cases the DT&E test conditions are conducted using straight and level flight conditions. This is done to focus the analysis on whether or not the jammer is performing properly. This is obviously not an operationally representative condition and the results are difficult if not impossible to extrapolate to draw quantifiable tactically relevant conclusions about the jammer's contribution to survivability. While operationally representative test conditions are generally not central to DT&E evaluations, they should be kept in mind.

No single MOP encapsulates the worth of a RFCM system. Even taken in aggregate it is difficult to make value judgments. Some MOPs such as those addressing track errors (azimuth, elevation, range and/or velocity), are quantifiable. However, while they provide good measures for evaluating radar performance, they don't directly relate to the ability of the weapons system to successfully engage a target. Other measures that focus on the success of the weapons engagement, such as miss distance, rely on fly-out simulations and their associated assumptions. Additionally, miss distance by itself doesn't directly address the success or failure of the weapon engagement; most RF missile warheads are proximity fused and the engagement geometry, fusing, and warhead characteristics significantly affect the engagement outcome. While missile miss distance produces a quantifiable result, a number of measures require the analyst to make a hit/miss determination and this involves a number of subjective judgments.

Analysts need to have a thorough understanding of how threat-radar systems work and operate in order to evaluate test results. As previously stated it is difficult to quantify a jammer's contribution to overall platform survivability. However, by evaluating a number of MOPs in aggregate, the analysts need to determine if the RFCM system is having the intended effect on each victim radar and whether or not the effect will be significant (even if it can't be quantified in terms of overall survivability).

3.3 SUPPORT JAMMERS

Support jammers perform offensive EA. They share many similarities in design and functionality with SPJ, but unlike the SPJ, a support jammer is primarily designed to protect other aircraft from the surveillance radars of hostile air defence systems while they conduct their missions. [1]

3.3.1 Support Jammer System Concepts and Operation

Support jammers perform three basic roles:

- **Stand-Off Jamming (SOJ)** – Normally performed by a manned aircraft operating outside the engagement range of hostile air defence systems;
- **Escort** – Normally performed by a manned aircraft accompanying a strike package; and
- **Stand-In Jamming** – Normally performed by unmanned expendable air vehicles operating within the engagement range of hostile air defence systems.

Figure 3-7 illustrates these roles.

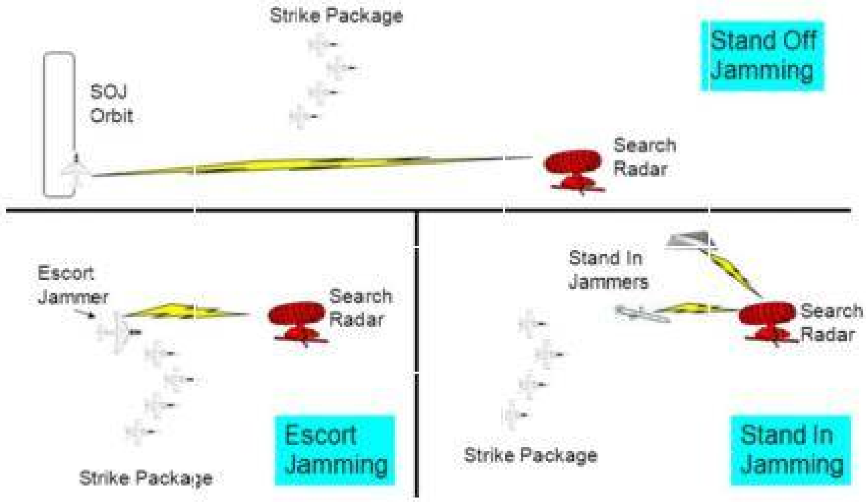


Figure 3-7: Different Types of Support Jamming.

Support jammers have the same functional elements as described in Section 3.2.2 and shown in Figure 3-3. These systems can be carried internally or externally on a manned aircraft. Commonly the receiver systems are internally mounted and the transmitters are carried in external pods as shown in Figure 3-8. Stand-in jammers are normally expendable and launched from a host platform. Figure 3-8 shows a Miniature Air-Launched Decoy (MALD). A special MALD variant, the MALD-J, performs stand-in jamming.

Figure 3-8: a) EA-6B Aircraft with External Jamming Pods; b) Miniature Air Launched Decoy Carried by F-16 – (U.S. DoD Photos).

Support jammers conduct EA operations primarily to deny, degrade, or delay the detection of friendly aircraft by the surveillance radars of an IADS. As with SPJ systems, it is important to understand the basic operation of the radar systems that the jammer attacks. Surveillance radars commonly scan a volume of airspace covering 360 degrees in azimuth, although some cover more limited sectors.

Surveillance radars report detected targets up echelon to the command and control elements of an IADS to aid in forming the air picture in one of two ways: an operator watching a radar scope manually identifies targets or a computer called a target extractor automatically identifies targets. Noise jamming is designed to raise the noise level in the victim radar's receiver thereby reducing the signal-to-noise ratio and decreasing the probability of target detection. False target jamming is designed to present the operator or the target extractor with a large number of false targets that cannot be discriminated from the real targets. Figure 3-9 shows the effects of noise and false target jamming on a Plan Position Indicator (PPI) displays.

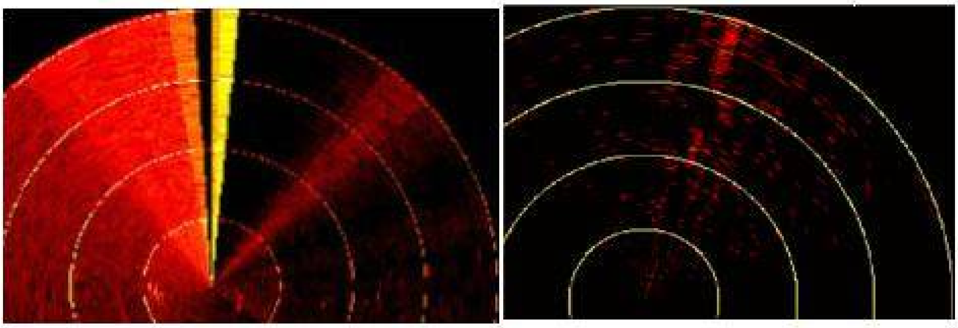


Figure 3-9: Effects of Noise and False Target Jamming on PPI Displays.

3.3.2 Support Jammer System Testing

Support jammer testing is in many ways similar to SPJ testing and most of the discussion in Section 3.2.3 applies. The following paragraphs address the areas that are unique to support jammer testing.

J/S ratio is also a critical measure for support jammers, but it is manifested differently. In the SPJ case, the main beam of the threat system TR radar is centred on the target it is tracking, allowing the SPJ to continuously direct most of its jamming energy into the victim radar's antenna main lobe. This maximises the jamming energy transfer by virtue of the geometry. In contrast, the support jammer normally operates against scanning radars antenna side lobes and can only jam into the victim radar antenna's main lobe when it is aligned with the jamming platform. Annex C develops the J/S expression for the support jamming case.

Jamming performance assessments against search radars are different for noise and deceptive techniques. This is because they are fundamentally attacking two different things. Ideally, a noise jammer raises the noise level in the victim receiver to the point that targets cannot be detected. In the ideal deceptive jamming case the victim receiver is presented with an overwhelming number of realistic false targets where the true targets cannot be discriminated.

Flight testing against high fidelity simulators or actual threat radar systems provides the highest level of fidelity when evaluating the jamming effects on an individual surveillance radar system. This environment provides actual radar clutter, multi-path effects, and operator displays.

Support jamming effectiveness against manned systems can vary significantly with operator skill level. One operator may be able to see targets in a high-level noise jamming environment while another may not. Similarly, some operators may be able to tell the difference between real and false targets while others may not.

ROE defining what EP features the radar operators will be able to use need to be clearly defined. The ROE relate to the specific objective that the test address.

3.4 RF TOWED DECOY SYSTEMS

Radio frequency towed decoys are defensive EA systems performing self-protection jamming. They differ from onboard SPJ in that they are countermeasures systems dispensed from the host aircraft either pre-emptively or automatically in response to a hostile radar threat engagement. They are towed behind the aircraft and designed to present a more seductive target to the hostile radar or missile seeker. Most towed decoys are expendable, although retractable models exist.

3.4.1 Towed Decoy System Concepts and Operation

A towed decoy has one significant advantage over onboard SPJ system. It is difficult for onboard SPJ systems to create angle tracking errors against monopulse radars. In the towed decoy case, if the radar or missile seeker is tracking the towed decoy, it is not tracking the targeted aircraft and there is an inherent angle tracking error.

There are two basic types of towed decoys. The first is a simple repeater that retransmits the targeting radar waveform at a higher signal level in order to seduce the track away from the target aircraft; it is essentially a beacon. Figure 3-10 shows a block diagram of a simple repeater. Once deployed the system only requires power and control from the host platform. When the system receives an RF signal via the towed decoy onboard receiver that meets the threat criteria, it amplifies and retransmits the signal in hopes of seducing the threat track.

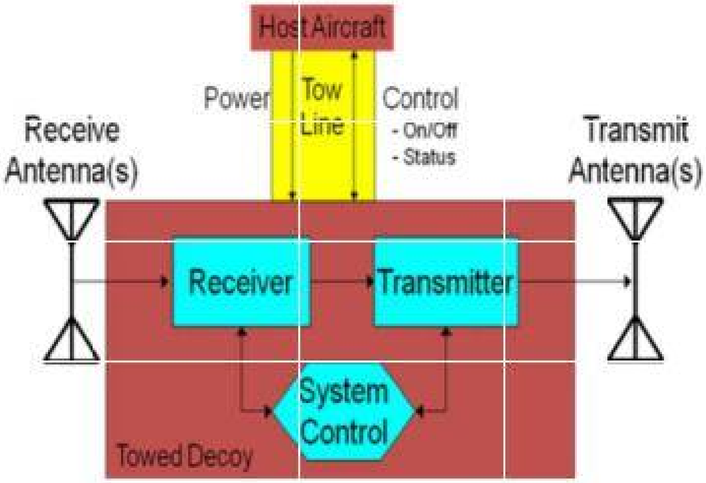


Figure 3-10: Simple Repeater Towed Decoy Block Diagram.

The second type are Fibre-Optic Towed Decoys (FOTDs). FOTDs employ sophisticated receivers and technique generators onboard the host aircraft. Figure 3-11 shows a block diagram of an FOTD system. The receiver systems associated with FOTDs are very similar to EW receivers discussed in Chapter 2. The onboard receiver passes threat information to the technique generator in a manner similar to the SPJ operation. It differs from the SPJ case in that it converts the RF technique to optical wavelengths and transmits it via fibre-optic cable to the FOTD where it is converted back to RF, amplified, and retransmitted.

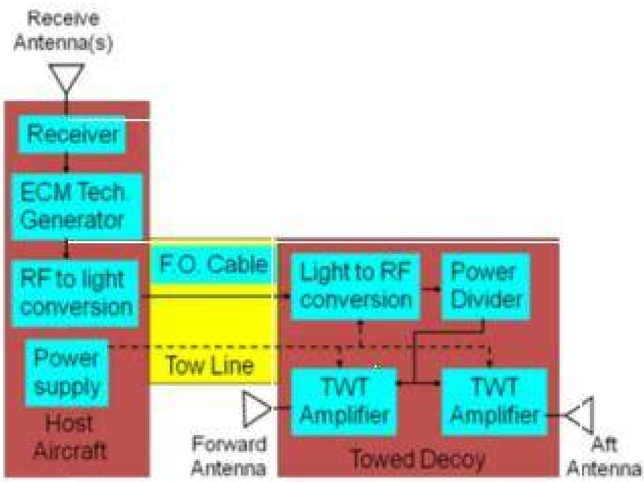


Figure 3-11: Fibre Optic Towed Decoy Block Diagram.

Both decoy types typically use Travelling Wave Tube Amplifiers (TWTAs), although Microwave Power Module (MPM) technology is now also used. Figure 3-12 shows a typical towed decoy.

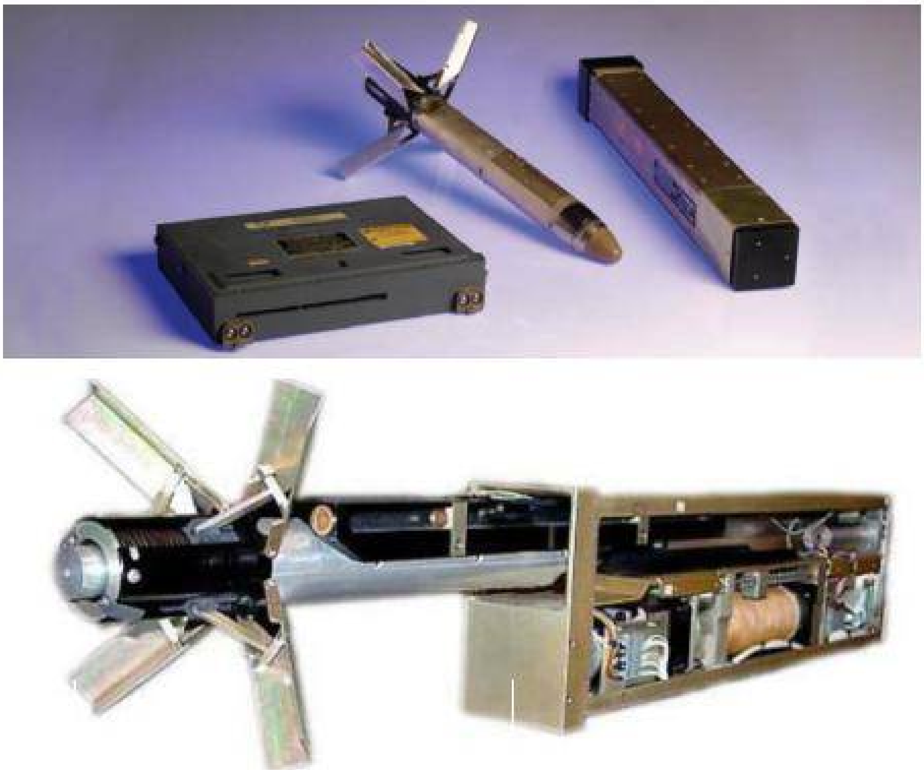


Figure 3-12: Typical Fibre Optic Towed RF Decoy – AN/ALE-55 – (BAE SYSTEMS Photo).

3.4.2 RF Towed Decoy Testing

All of the discussions in the EW RF receivers test section apply to towed decoys and the technique generation testing is similar to the SPJ testing. The major difference is that the decoy must properly deploy in a timely manner. Decoy deployment is a complicated process, as is retraction, for those systems with that capability.

3.4.2.1 Uninstalled Towed Decoy Component Testing

All of the concepts associated with testing RF receivers, signal processing, and technique generation also apply to towed decoy development and testing. M&S can be used to evaluate the aerodynamic separation characteristics as well as the performance and effectiveness of the towed decoy system.

One of the most challenging aspects of towed decoy development is the mechanical deployment (and possibly retraction) of the device. Flying test beds provide the system developers an opportunity to collect data under a variety of flight conditions.

3.4.2.2 Installed Towed Decoy Testing and Performance Assessments

Towed decoy deployment from a flying test bed provides an excellent opportunity to develop the system and reduce risk. However, the flying test bed is likely to have a significantly different aerodynamic and vibro-acoustic environment and towed decoy separation characteristics than the production airframe. The decoy needs to cleanly separate or it may damage the host aircraft and/or the decoy. Decoy deployment testing should be conducted throughout its required operating envelope to determine any deployment or towing limitations.

Fully functional towed decoy rounds are expensive and are generally not required to evaluate separation and deployment characteristics. Towed decoy mass models have the same weight and balance and aerodynamic characteristics as an actual round without any of the expensive electrical components.

Towed decoy deployments happen rapidly and high speed cameras installed at one or more locations on the host aircraft can document the towed decoy separation from the aircraft. Safety and photo chase are also very useful in case there is a deployment mishap.

Reactive towed decoy systems need to deploy the decoy to its full deployment length in a very short time and operate properly when it gets there. The mechanical braking system and associated algorithms must be evaluated to ensure they work properly. If too much breaking force is applied, the decoy will take too long to deploy. If too little braking force is applied near the end of the deployment, the sudden stop may subject the towline to a load that will cause the towline to fail and the decoy to break away. A properly instrumented decoy system will greatly aid in deficiency investigations.

Towed decoy systems present several test safety considerations. The towed decoy rounds typically use pyrotechnic charges to initiate the decoy deployment and to sever the round when it is no longer needed or if it has malfunctioned. An armed towed decoy round is a munition and need to be treated with all the appropriate safety precautions.

Towed decoys can inadvertently separate from the host aircraft and present a risk to personnel on the ground. Developmental towed decoy operations should take place over controlled ground ranges to ensure personnel and high-value material will not be put at risk if a decoy malfunction causes an unplanned separation.

3.5 ACTIVE INFRARED COUNTERMEASURES SYSTEMS

Conventional active IRCM systems are electrically powered defensive EA systems designed to protect aircraft from IR-guided missiles. There are several types of IRCM systems. The simplest is a ‘turn on and forget’ system that uses a modulated IR jamming waveform that transmits continuously over its field of view. Figure 3-13 shows a typical undirected IRCM system installation.

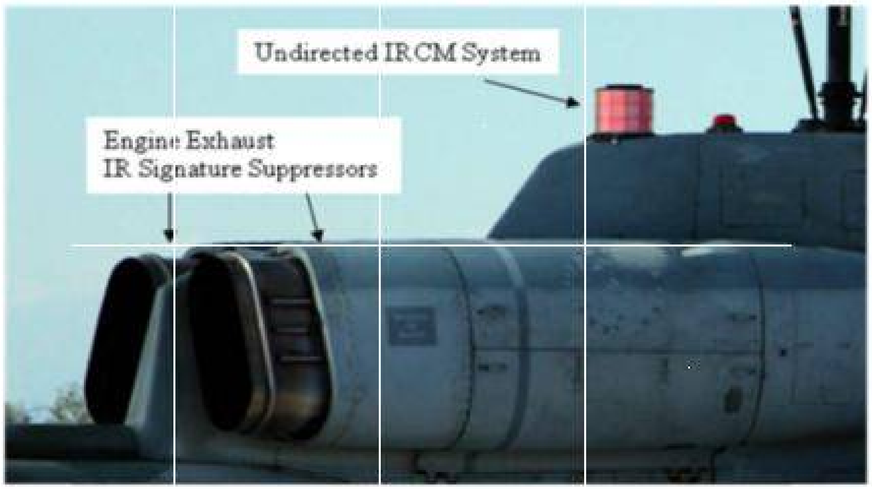


Figure 3-13: AH-1 IRCM Installation and IR Signature Suppressors – (U.S. DoD Photo).

More sophisticated IRCM systems, often called Directed IRCM (DIRCM) systems, are turret mounted and receive cuing information from MWS. These systems typically use either arc-lamp or laser-generated AM jamming waveforms. Laser-based systems have the advantage of directing significantly more energy into the victim missile seeker. Figure 3-14 shows a typical DIRCM installation.

Figure 3-14: Department of the Navy Large Aircraft Infrared Countermeasures Installation on a CH-53E Helicopter – (U.S. Naval Air System Command Photo).

DIRCM systems typically receive cuing from an MWS and slew a turret assembly (an aircraft may employ several turrets to achieve the required spatial coverage) toward the threat missile. Each turret has a fine-track sensor that will then take over tracking (as with the MWS, the fine-track sensor also tracks the missile plume) the inbound missile and direct the countermeasure transmitter or laser toward the missile seeker. The DIRCM transmitter or laser is boresighted to the fine-track sensor, such that the jamming energy is directed along the line of sight of the fine-track sensor toward the missile seeker. Figure 3-15 shows a typical DIRCM engagement sequence.

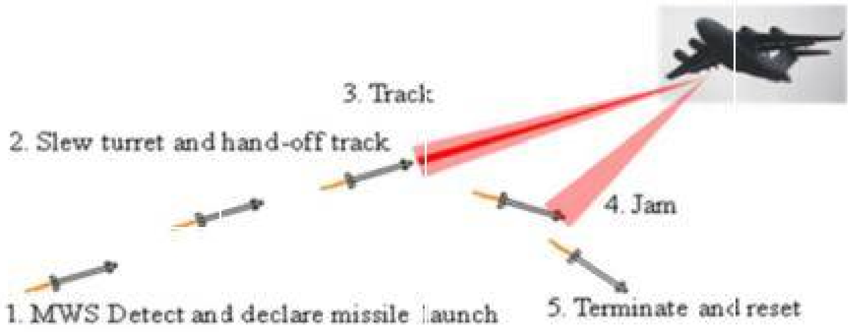


Figure 3-15: DIRCM Event Sequence.

IRCM performance can be enhanced by reducing the IR signature of the target aircraft. This can be accomplished by a variety of means, including installing engine exhaust suppressers as shown in Figure 3-13 or by using low-IR-signature paint on the aircraft fuselage. To further enhance IRCM performance, flare expendables are often used with IR jammers.

3.5.1 Active IRCM System Components and Operation

The following sections address the components of a typical active IRCM system. The MWS portion of DIRCM systems is addressed in Section 2.3.

3.5.1.1 Countermeasures Codes

The 'processor' of an IRCM system is a modulated power supply that drives the transmitter. Through threat analysis or exploitation, the scanning frequencies of the missile-tracking circuits are determined and these frequencies are programmed into circuitry used to modulate the power supply. The modulated power supply is either present as standalone hardware in the cargo bay area or integrated in the transmitter. In both cases, manual switches are present to allow selection of pre-programmed jam codes. Additional IRCM codes can be pre-programmed as new threats are defined.

3.5.1.2 Controls and Displays

The pilot interface is through a control indicator located in the cockpit. The pilot control indicator is either a standalone module for the IRCM system or it is shared with another EW system. The interface is usually quite simple, only providing a means of turning the system on or off and a way to alert the pilot that a malfunction has occurred.

3.5.1.3 Transmitter

There are several methods to generate the required IRCM pulses. One technology uses heated carbon-material rods and mechanical modulation techniques to generate the pulsed IR radiation to deceive the incoming missile seeker. Another technology uses an arc lamp in a vacuum tube, which is electronically modulated to provide the required pulsed IRCM radiation. Lasers are becoming the IRCM transmitter of choice due to their ability to inject high energy jamming into the missile seeker.

The basic undirected IR transmitters usually have a wide field of view (180 to 360 degrees in azimuth) and are typically located as close to the engine exhaust as possible since most of the IR threat missile seekers tend to initially acquire and lock onto this 'hot spot.'

DIRCM systems employing arc lamps and lasers focus their energy toward the homing missile seeker. The laser systems employing coherent energy have very small beam divergence and can direct significant energy into the victim seeker. The arc lamp will spread its energy over a wider field of view resulting in lower energy levels incident on the victim seeker detector.

3.5.2 IRCM System Testing

As with RFCM systems, the chief concern for IRCM systems is the degree to which they enhance the survivability of the host platform. Similarly, missile miss distance is a key consideration in evaluating the effectiveness of the IRCM system. There are several factors making the IR case somewhat easier to evaluate. First, once launched, IR missiles do not have an operator in the loop. Unlike the RFCM system, the IRCM system is an open-loop system; it does not get feedback from the system it is jamming (the missile seeker is a closed-loop tracker and the focus of the evaluation). Also, live-fire events are somewhat less costly and more practical.

A major figure of merit for IR jammer effectiveness is the J/S ratio that the system can achieve. Specifically, the higher the amount of modulated radiation output (provided by the jammer) over the host aircraft signature, the better the IRCM performance will be in countering the threat of the same IR spectral bandpass.

An end-to-end flight test of an integrated MWS and DIRCM system would require live-fire missile launches at a drone aircraft carrying these systems. While this is feasible and potentially desirable, there are other ways to evaluate the performance of these systems. Testing can be broken down into two parts: the missile launch detection and hand-off information accuracy (see Section 2.3.2), and the IRCM effectiveness. These two pieces can be tested and evaluated independently. The first evaluation addresses whether or not the MWS can quickly and accurately detect and hand off the engagement to the fine-track sensor. Once the fine-track sensor has acquired the missile, the IRCM will be directed in an open-loop fashion at the missile seeker.

3.5.2.1 Uninstalled IRCM System Component and System Level Testing

The jammer spectral and temporal signatures can be measured with great precision and accuracy in a laboratory and the host aircraft signature can be measured in flight. In-flight signature measurement with ground-based or airborne radiometers requires accurate range to the target and angle information and meteorological conditions (barometric pressure, ambient temperature, and relative humidity) to account for atmospheric transmissivity. The J/S of the host aircraft can be calculated when the jammer characteristics and the aircraft signature are known.

HITL facilities provide an excellent venue to develop and evaluate IRCM techniques. These facilities allow evaluation of the effects of the actual IRCM transmitter, such as a laser, on actual seeker hardware. A highly instrumented seeker installed on a full-motion flight table, such as shown in Figure 3-16, supporting a high-fidelity missile fly-out model, tracks a dynamic simulated target in an IR scene. The laser countermeasures are injected into the scene through a series of folded optics. This presents a realistic target scene with both the simulated target IR signature and the IRCM energy concurrently being presented to the missile seeker. This allows a wide variety of conditions to be evaluated in a short time.

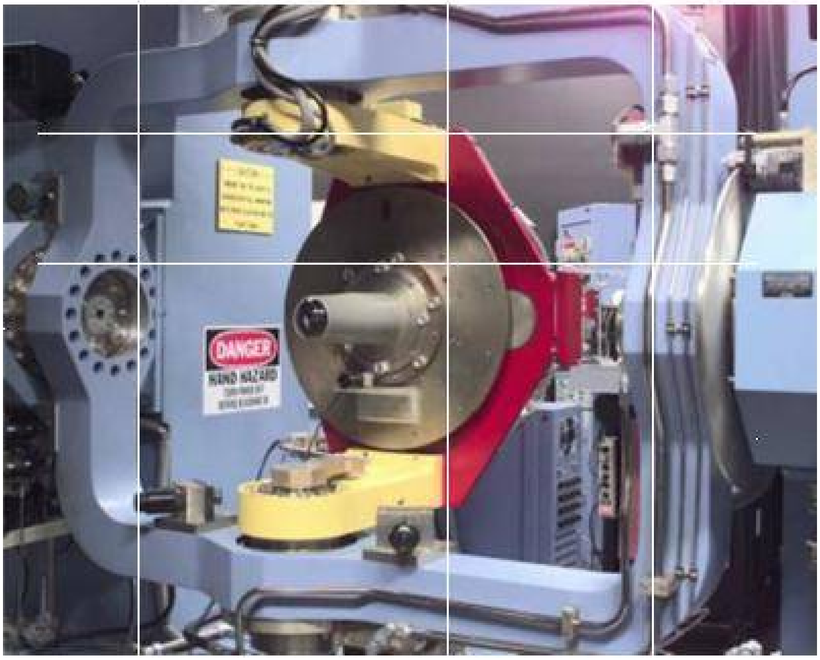


Figure 3-16: IR-Guided Missile Seeker Mounted on Full Motion Simulator – (U.S. DoD Photo).

An end-to-end system test can be accomplished using the cable car testing addressed in Chapter 2. In this case the instrumented MWS is integrated with the instrumented IRCM system and a live missile launch is directed at the cable car. The MWS can be evaluated on its ability to detect the launch and hand off the track and the IRCM system can be evaluated on its ability to acquire the missile and counter it.

One of the most complete and correspondingly expensive means of evaluating IRCM performance is live-fire testing. Live-fire evaluations can be conducted by installing an instrumented (preferably with telemetry capability) IRCM system, or IRCM and MWS system in the integrated case, on a drone aircraft and a true end-to-end engagement can be considered. The cost of certain IR-guided missiles is relatively low and this can be a cost-effective means of testing the IRCM system. However, the cost effectiveness of the test is directly related to how well the IRCM system performs. The cost planning needs to account for the possibility that the IRCM system is ineffective or malfunctions, resulting in the loss of drone and SUT.

3.5.2.2 Installed IRCM System Testing

There are several common methods of evaluating IRCM system performance in flight test. Each has advantages and disadvantages. Much of the DIRCM installed system testing is done in flight, providing an end-to-end evaluation incorporating the actual target aircraft signature. End-to-end testing requires three things, the ability to:

- Simulate a valid missile launch and generate an MWS missile launch declaration;
- Determine if the IRCM has been properly directed; and
- Assess the effectiveness of the IRCM on actual missile seekers.

Ideally, the test aircraft will be instrumented to record the MWS missile detection and declaration data as well as the hand-off and IRCM turret pointing data. The JMITS shown in Figure 2-17 and Figure 3-17 incorporates all of the elements necessary to perform end to end testing. Figure 2-17 shows the high fidelity JMITS IR/UV missile plume simulators and Figure 3-17 shows the JMITS laser radiometers used to detect the IRCM response and the instrumented missile seekers. The capability to record the IR signature of the test aircraft with ground-based radiometers is also desirable.

Figure 3-17: Joint Mobile IRCM Test System – (U.S. DoD Photo).

Static, ground-mounted, seeker-based test systems have the advantage of using actual instrumented seeker hardware tracking the host aircraft against which the IRCM performance can be evaluated. There are, however, several disadvantages that need to be considered during test design. First, the test aircraft flight profile must be designed to ensure that MWS doesn't reject the launch simulation based on engagement kinematics. Second, static missile seekers do not have realistic motion associated with an actual missile fly-out. Specifically, the missile isn't closing on the target at a realistic rate and doesn't have to react to the high angular rates of change associated with a real engagement, particularly at endgame.

3.6 COUNTERMEASURES DISPENSING SYSTEMS

CMDS are most commonly employed in a defensive electronic attack role. They dispense expendable payloads to deceive hostile air defence weapons systems. Conventional chaff and flares are the most common payloads and some CMDS are also capable of ejecting expendable (non-towed) RF decoys.

Chaff is one of the oldest forms of radar electronic countermeasures. It consists of a large number of micro-fibre reflective dipoles. When dispensed it disperses in the air stream forming a cloud and presenting the hostile radar with other competing large RCS targets. Figure 3-18 shows a typical round assembly and chaff fibres.

Figure 3-18: Typical Chaff Rounds and Chaff Dipoles – (U.S. Navy Photo).

Flares are pyrotechnic devices designed to deceive IR-guided missiles by presenting the missile seeker with a more attractive target than that the target aircraft. Conventional flares are made of various combinations of magnesium, phosphorus, and Teflon which is ignited when the flare is dispensed from the magazine and tries to mimic relevant spectral aircraft engine characteristics. Figure 3-19 shows F-16 and AC-130U aircraft dispensing conventional flares.

Figure 3-19: Flare Dispensing by F-16 and AC-130U Aircraft – (U.S. DoD Photos).

Flare technology continues to adapt to keep up with the advancing threat. Conventional flares are highly visible in the visual portion of the electromagnetic spectrum and can give away the position of an aircraft, particularly at night. To alleviate this problem, flares with minimal visual signature have been developed that still retain the required IR signature characteristics. Kinematic flares have also been developed to overcome the kinematic EP logic in some modern threat missile seekers. These essentially fly along with the aircraft as they separate and have a less abrupt angular separation from the host aircraft.

3.6.1 CMDS Components and Operation

CMDS are commonly installed in an integrated configuration and receive threat-related information from RWR and MWS to optimise dispense patterns and enable automatic operation. Most have three modes:

- **Manual** – Aircrew-initiated programmed response;
- **Semi-Automatic** – Automatically generated response requiring aircrew prior consent; and
- **Automatic** – Autonomous operation, i.e., without aircrew input.

A typical CMDS comprises a Cockpit Control Unit (CCU), a programmer, sequencers, the dispenser and magazine, and a safety switch. Figure 3-20 depicts these components and their functions.

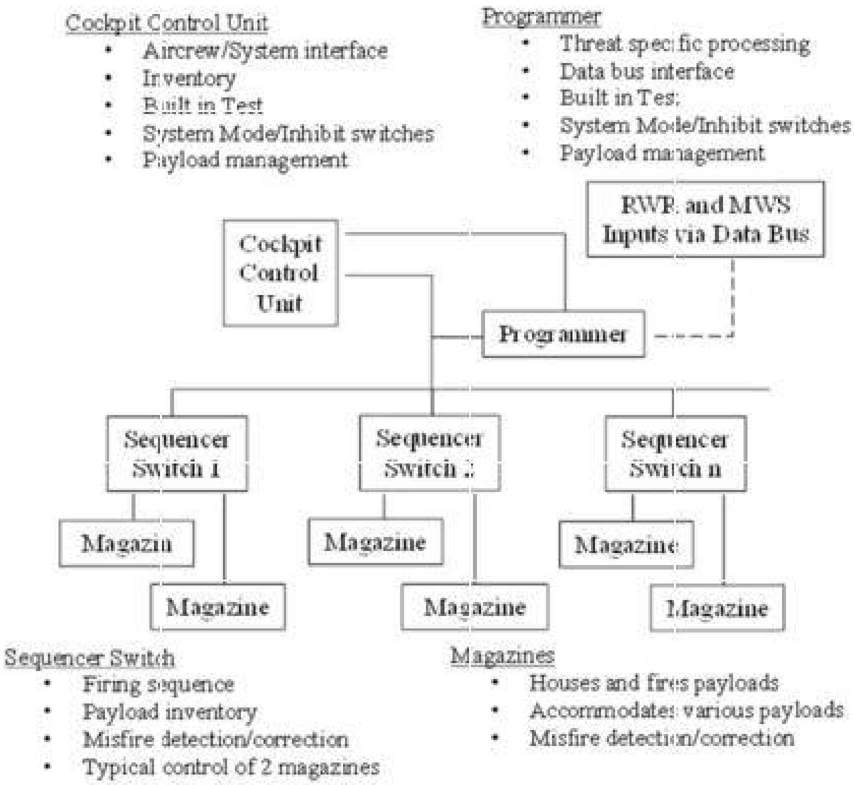


Figure 3-20: Block Diagram of Countermeasures Dispensing System.

Figure 3-21 indicates these components in a typical CMDS.

Figure 3-21: Typical CMDS – AN/ALE-47 – (Symetrics Industries Photo).

3.6.1.1 Control Unit

The CCU is the aircrew interface with the CMDS. It allows the operator to select the system mode, determine the remaining inventory, and programme the manual dispense parameters. The manual dispense parameters include the number of rounds in a burst and the time intervals between bursts. Other functions accessible through the CCU include the built-in-test and jettison. In many systems these features can be integrated with the avionics system and can be accessed via a glass cockpit.

3.6.1.2 Programmer

The programmer is the CMDS processor where both OFP and MDF reside. It typically receives threat data inputs via a data bus from the MWS and the RWR. The RWR typically provides threat specific data that along with aircraft airspeed and attitude data are used to optimise the response. The threat data consist of the parametric data that define the threat system. Pulse width, RF frequency range, amplitude or scan modulation, and pulse-repetition frequency are typical RF-threat parameters. Response data involve the specific dispensing technique against a known or identified threat. Responses consist of IR expendables, RF expendables (chaff), or a combination.

Dispense techniques are defined by the quantity and intervals at which the expendables are deployed. Payload data identify the types of expendables loaded into the dispenser and are available to be dispensed. During flight, the system monitors the magazine to keep track of how many and what type of expendables remain.

3.6.1.3 Sequencer

Sequencers distribute power and commands to dispensers. They manage payload inventories and determine if a misfire has occurred. Typically, one sequencer is used for every two dispensers.

3.6.1.4 Dispenser

The dispensers are housings for the magazines and are installed in the aircraft at the location where the expendables are to be released. The magazines are the modules that actually hold the expendables. Dependent upon expendable origin, preparation may be required prior to insertion into magazines:

- The US normally procures squibs (the pyrotechnic firing mechanisms) and flares separately, and these are not combined until shortly before use. They are inserted into the magazine, one squib for each expendable, prior to inserting each expendable.
- European manufacturers generally supply expendables with squibs ready fitted.

Squibs can only be used once and must be replaced like the expendables. Expendables are then loaded into the magazines in a safe area and then an entire magazine is inserted into a dispenser housing before each flight. Typical magazines on tactical aircraft hold approximately 30 expendables each. Figure 3-22 shows a typical CMDS dispenser with magazines installed.

Figure 3-22: CMDS with Magazines Installed on a C-130 – (U.S. DoD Photo).

The safety switch is an important part of the CMDS. When engaged, it does not allow any current to reach the dispenser, thus eliminating the chance of a squib accidentally firing.

3.6.1.5 Expendables

Expendables payloads are generally not produced by the CMDS manufacturer. All CMDS support conventional chaff and flare rounds. Many support other advanced payloads such as kinematic flares. Chaff, flare, and other advanced expendable rounds, including RFCM, are continuing to evolve and the CMDS must be able to accommodate them. The expendable payload manufacturers design their products to be compatible with existing dispensers. CMDS OFP and MDF changes may be required to accommodate new expendable products. Figure 3-23 indicates typical flare and chaff cartridge used across NATO. [2]

Flare Cartridges: 36 mm, 2 x 2.5, 2 x 1, 1 x 1; and their associated impulse cartridges

Chaff Cartridges: 36 mm, 1 x 1 (dual), 1 x 1 (Standard) and their associated impulse cartridges

Figure 3-23: Examples of Expendable Configurations Within NATO (From [2]).

3.6.2 CMDS Testing

CMDS and airframe designers and developers extensively employ M&S to explore the critical question of where the CMDS dispenser should be installed on the host airframe. This is a particularly important consideration for flare dispensers. High fidelity aircraft structure and signature models allow designers to evaluate a variety of potential installations and their associated payload trajectories against the models of the threats of interest under a variety of engagement geometries.

Much of the CMDS and payload development testing can be conducted independently and concurrently for new systems. However, the CMDS and payload combined performance and effectiveness can only be evaluated in flight with the CMDS installed on the intended host platform using the intended payloads. This allows the payload effects to be evaluated with actual aerodynamic and host aircraft signature characteristics.

3.6.2.1 Uninstalled CMDS Testing

3.6.2.1.1 CMDS Component Testing

Hardware laboratory testing includes verifying that each separate CMDS module functions properly and operates within design parameters. Power, continuity, voltage, and Built-In Tests (BITs) are performed. These tests help to isolate hardware configuration or interface problems.

Software laboratory tests are performed on each module containing software. These tests help isolate any programming or timing errors and verify that the system software has been correctly implemented. Such errors can impact not only system performance, but may affect safety and survivability. Manual and automatic dispense capabilities are also evaluated to verify performance.

3.6.2.1.2 CMDS Level Testing

When the performance of the individual components has been verified, the CMDS can be tested as a complete system. Unlike many other EA systems the CDMS system does not have associated sensors. However, it does communicate via data buses with sensor systems such as RWR and MWS. Emulated data bus messages are generally sufficient to evaluate system level performance and laboratory RF threat simulation is generally not required for initial system level testing.

System level CMDS testing also verifies the proper operation of all operator switch settings. All system modes of operation can be tested in conjunction with a wide range of emulated RWR and MWS data bus messages. The dispenser assemblies are monitored to ensure that the proper firing pulses are generated in response to the test conditions.

Integration testing is the next stage of testing. It is conducted with the complete CMDS installed in a laboratory environment connected to actual avionics and EW hardware with representative aircraft cabling. This type of testing allows end-to-end system integrated system evaluations where the RWR is injected with simulated RF threat signals and/or the MWS sensors are stimulated. The data bus message traffic and the CMDS responses are monitored and recorded to verify proper operation.

Cable car testing is an effective means to evaluate end-to-end system level flare performance against actual missiles. The MWS and CMDS are integrated and installed on a cable car, see Figure 3-24. The number of flares dispensed and the timing between them is critical. This type of testing allows analysts to optimise system performance by evaluating the effects of number of bursts and timing intervals.

Figure 3-24: Flare Testing Using a Cable Car – (U.S. DoD Photo).

3.6.2.1.3 Expendable Payload Testing

Expendables are tested to verify that they meet their design specifications and requirements. Key IR expendable parameters include time to ignite, total burn time, spectral signature content, and intensity. RF expendables are tested to measure RCS "bloom" rate, which is how fast the expendable can achieve the desired RCS, fall rate, and actual frequency range over which the RCS can be achieved.

A single type of expendable payload will likely be employed on a variety of host aircraft and each dispenser installation will have unique separation characteristics. Additionally, many platforms employ a variety of expendable payloads. Software modelling should be performed to predict the separation characteristics for each type of expendable round that will be employed.

3.6.2.2 Installed CMDS Testing

3.6.2.2.1 Ground Testing

During installed-system test facility testing, dispenser systems are installed on a production representative aircraft and all functional tests are repeated to verify the system operates properly. These tests are conducted to verify electrical, mechanical, software, and EMC/EMI functionality and performance.

When EMI/EMC testing is conducted in an anechoic chamber where munitions cannot be used CMDS maintenance test sets can often provide a suitable means of monitoring the CMDS dispenser firing commands. It is critical to verify that the system will not inadvertently dispense its payload when operating in the presence of onboard RF transmitter or anticipated external RF transmission sources.

3.6.2.2.2 Flight Testing

The first consideration in CMDS flight testing is evaluating the expendable separation characteristics throughout the required flight envelope. It is important to verify, for example, that flares do not strike the airframe. Separation testing should be performed using a build up approach. The build up begins with test points where the modelling predictions show the largest separation margins and progresses toward the test conditions with the smallest margins.

Cameras mounted externally on the host platform can document separation characteristics for post-flight analysis. Chase aircraft perform several important roles during separation testing. First, the chase aircraft aircrew can provide real-time observations regarding the expected separation margins to the test conductor.

If the margins are less than expected the test team may decide to terminate the test and re-evaluate the predictions. Second, if a round strikes the dispensing aircraft the chase aircrew can advise the test aircraft aircrew about the condition of their aircraft. Finally, the chase aircrew can provide additional photographic documentation about the separation events.

CMDS performance and payload effectiveness are evaluated by testing against ground-mounted missile seekers and radiometric measurement systems, airborne pod-mounted missile seekers and radiometric measurement systems, and live-fire testing as discussed in active IRCM section. Figure 3-25 shows the Airborne Turret IR Measurement System III (ATIMS III) carried by an F-15 conducting a test on an F-18 aircraft dispensing flares. The ATIMS III pod carries up to four fully instrumented missile seekers.

1. Seekers
2. Mid-IR Imager
3. Televisions
4. Laser

Figure 3-25: Airborne Turret IR Measurement System III – (NAVAIR Photo).

3.7 LOW OBSERVABLE SYSTEMS

LO technology is a passive form of EA and has become a significant contributor to aircraft survivability and mission effectiveness. RCS and IR signature are the two areas most relevant to EW T&E. Signature reduction reduces the detectability of the subject aircraft. It also benefits any aircraft employing or benefiting from RF or IRCM, as the lower signature results in higher J/S ratios at the victim sensor.

3.7.1 LO Concepts

The most important RCS consideration in aircraft design is vehicle shaping. The air vehicle is designed to minimise the incident energy that is backscattered toward the radar, that is, the energy is directed in another direction. RAM is also applied to the surfaces of the vehicle to dissipate incident radar energy. There are RCS reduction techniques to address major scattering sources such as cockpits, engine inlets and exhaust, antennas, etc. Aircraft canopies can be coated with conductive material such that incident RF energy does not enter the cockpit. Engine turbo machinery is a major scattering source and inlet/ exhaust designs that minimise their visibility to threat radars have proven effective. There are specially designed LO antennas to minimise their contribution to the overall RCS.

There are also a number of ways that aircraft designers can reduce an aircraft's susceptibility to IR-guided missiles. Shortwave-IR missile seekers track hot metal parts such as engine exhaust nozzles. Engine installation designs that prevent an IR missile seeker from having a line of sight to hot metal parts can significantly reduce the susceptibility of an aircraft to IR-guided missiles. Longer-wave IR missiles track the aircraft engine exhaust plume, and mixing cooling air into the exhaust can reduce the signature of the aircraft in the longer wavelengths. The signature of existing airframes can also be reduced by adding signature suppressers that either block the line of sight to hot metal parts or provide mixed cooling air. Add-on IR signature suppressors can adversely affect aircraft weight and performance.

3.7.2 LO Systems T&E

3.7.2.1 M&S

3.7.2.1.1 RCS Prediction and Mission Effectiveness Assessment

M&S plays a key role throughout the design and development of an LO air vehicle. The two interrelated areas where M&S play important roles are signature prediction and mission effectiveness assessment. Early in development, sophisticated software design tools can be used to conduct trade studies and predict the signatures of candidate aircraft designs. The modelled signature and predicted aircraft performance characteristics can be inputs to mission-level modelling simulating relevant missions to evaluate the effectiveness of the system.

M&S is also used to estimate mission effectiveness. The ability of search radars and radar-directed air defence weapons to detect and engage the air vehicle are established through engagement level modelling. These modelling efforts produce detection contours for search radars where the detection ranges are established as a function of aircraft aspect angle. The engagement modelling against terminal threat systems produces probability of kill (P_k) grids, where the P_k is established for each threat system of interest as a function of range, aircraft aspect, and flight conditions.

An acquisition programme commonly establishes operationally representative mission scenarios against which the aircraft performance will be evaluated. The results of the engagement modelling are incorporated with modelled command and control elements of a hostile air defence system to evaluate aircraft survivability in the reference scenarios. M&S is repeatedly performed as the design evolves to estimate the effects of design changes on performance.

The accuracy of RCS data will improve throughout the programme. Initial modelling will be based solely on digital RCS predictions. As the design matures static RCS measurements are made on major component assemblies as well as sub-scale or full scale aircraft models at measurement facilities. Finally, when actual aircraft are available, in flight RCS measurements of the actual air vehicle can be performed.

3.7.2.1.2 IR Signature Prediction and Detection Assessment

M&S also plays a significant role in IR signature prediction. IR aircraft signature modelling must account for a number of factors, such as engine settings, aerodynamic heating, and solar glint. The resultant model provides a database of IR spectral radiant intensity as a function of wavelength and aircraft aspect angle that can be used in engagement level modelling. Once the IR signature of the air vehicle has been modelled, further M&S is conducted to evaluate the ability of IR sensors and guided weapons systems to detect, track, and engage the air vehicle. Atmospheric conditions have a significant effect on IR transmissivity and the model must account for factors such as humidity and particulate matter.

3.7.2.2 Signature Measurement

3.7.2.2.1 RCS Measurement

Ground-based RCS measurement facilities support LO platform design and development by providing measured RCS data on either scale or full-sized models. These facilities allow designers to optimise platform signature during development and provide analysts with high fidelity data to support mission effectiveness M&S. RCS measurements are performed on pole-mounted models. The models can be positioned in azimuth and elevation such that the RCS can be measured at each aspect of interest. Precisely calibrated radars measure the RCS of the model at relevant frequencies and polarisations. Figure 3-26 shows an F-35 model undergoing RCS measurements. Figure 6-1 shows another type of ground test capability for the measurement of RCS of real aircraft.

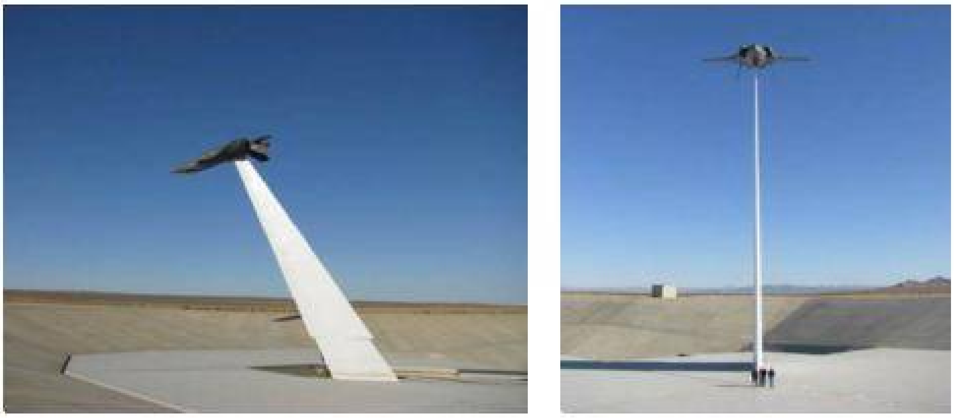
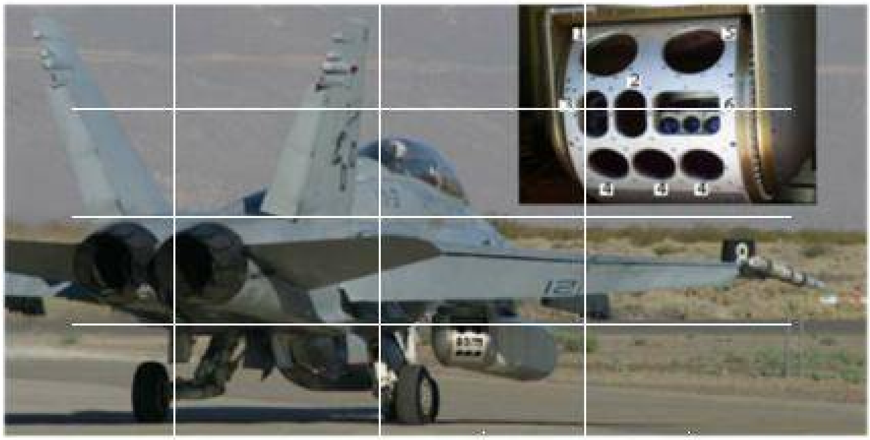


Figure 3-26: F-35 Model Undergoing RCS Measurements – (Lockheed Martin Photos).

In-flight RCS measurement facilities, such as the Patuxent River Atlantic Test Range, are used to collect data on actual aircraft. Specialised flight profiles are flown against ground-based precision measurement radars. Flight profiles are designed to maintain the proper geometric alignment between the measurement radar and test aircraft such that the RCS measurements are collected at the required frequencies, polarisations, and azimuth and elevation angles.

3.7.2.2.2 IR Signature Measurement

The IR signature of an aircraft can be measured in flight either using ground-based or airborne measurement systems. Airborne systems have the advantage of being able to measure the signature at fixed points around the platform. Figure 3-27 shows the Threat IR Generic Emulation Radiometer (TIGER) Pod which can provide all aspect air-to-air signature measurement of fixed and rotary wing aircraft and IRCM flares.



1. Long Wave IR Camera
2. IR Tracking Camera
3. Laser Range finder
4. Mid-IR Camera
5. Mid-IR Spectrometer
6. Televisions

Figure 3-27: Air-to-Air TIGER Pod Mounted on F-18 – (NAVAIR Photo).

Measurements should be made at all relevant aircraft conditions. The various engine throttle settings can affect the IR signature of the aircraft. Aerodynamic heating related to airspeed also affects the aircraft's IR signature. The IR signature of an aircraft can, with limitations, be measured using MFs similar to that shown in Figure 6-1.

3.8 DIRECTED ENERGY SYSTEMS

DE weapons are, by definition, EA systems because they use DE "to attack personnel, facilities, or equipment with the intent of degrading, neutralising, or destroying enemy combat capability." [1] Two major DE areas are HPM and HEL systems. The potential advantages of DE include:

- Speed-of-light delivery;
- Invisible propagation;
- Directionality;
- Agility for engaging multiple targets;
- Deep magazines; and
- Immunity to the effects of gravity.

Disadvantages include:

- Attenuation with distance;
- Absorption by the atmosphere and moisture;
- Blockage due to weather;

- Complexity and sophistication; and
- Line-of-sight path to the target generally required.

The path to the target includes propagation physics. Propagation is a key consideration for effective use of both HPM and HEL weapons. HPM weapons tend to provide a soft-kill, or a disruption or denial effect, whereas HELs tend to be hard-kill devices.

3.8.1 HPM Systems

HPM weapons are systems that emit RF energy at high peak power levels and are often categorised by the bandwidth-to-frequency ratio of their waveforms. These are typically very large ratios. They have been divided into narrowband, wideband, and ultra-wideband. Peak power levels may exceed a gigawatt, but average powers may be less than a kilowatt. Some of the lower-frequency HPM devices have been called synthetic or non-nuclear Electromagnetic Pulse (EMP) or High-altitude EMP (HEMP). HPM devices have a smaller effective range than the EMP effects of a nuclear weapon. Narrowband devices tend to operate on specific electronic vulnerabilities in the target and therefore require knowledge of enemy systems to be effective. Ultra-wideband devices tend to be simpler and cheaper, using powerful transient waveforms, and requiring less knowledge of the target. A few HPM weapons function by making use of psycho-sensory or neural phenomena, rather than just high power levels, to deter human actions or cause confusion among attacking troops.

3.8.1.1 HPM System Components and Operation

Figure 3-28 illustrates the basic elements of an HPM-type system. Controls may include on/off, output level and repetition rate selections. Displays may be limited to input power indications or may include some feedback from the output, providing output waveforms and power estimates. Prime power is often electrical or chemical, or both. Pulse power may be provided by an explosive, one-time burst to effect dielectric, magnetic, or ferromagnetic generation of high voltages and currents; by a discharge of capacitors through spark-gaps, or through the use of special, high-power modulation circuits coupled to large special-purpose vacuum tubes. The output waveform must be matched to an antenna for energy transfer efficiency. Voltages are very high, requiring attention to air and dielectric material breakdown.

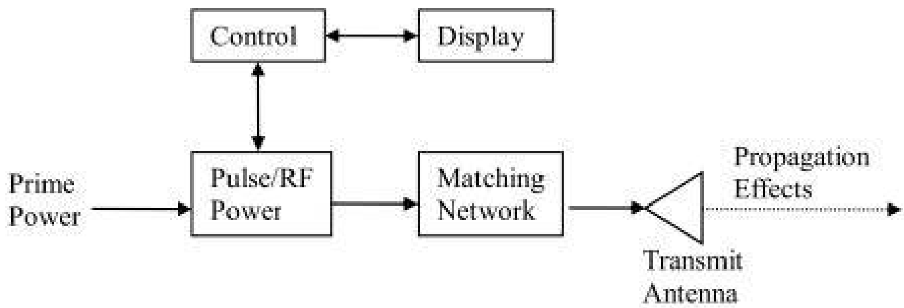


Figure 3-28: Simplified HPM Weapon/Source Block Diagram.

3.8.1.2 HPM System T&E

HPM weapon performance testing may include measuring performance metrics or confirming the lack of degradation of specific parameters, such as, the following:

- Power;
- Efficiencies of the pulse power conversion and RF conversion;
- Losses in the path to the antenna;
- Antenna gain or directivity; and
- Beam intensity.

Ultimately, performance comes down to an effect on enemy systems or forces. Operational performance can be summarised by the ability to create an effect, probability of effect (P_e). Those effects can be:

- Damage to a circuit;
- Upset of a system;
- Disturbance or denial of use of a system; and
- Interference while trying to employ a system.

The probability of an effect is often plotted as a family of curves against incident power levels. P_e is the most important parameter for weapons T&E. The other parameters are important for the engineering tasks of design and modelling.

Range is very important for mission planning, and can usually be derived from the parameters listed above for a particular desired effect, but may also include antenna gain as a function of angle from the source.

The often specialised nature and unique designs for DE weapons means that testing will differ between systems. Some of the common T&E approaches for DE systems are discussed in the following sections.

3.8.1.2.1 M&S

M&S is an important part of design, testing and usage of HPM weapons due to electromagnetic propagation phenomenology. Safe and effective testing cannot be performed without accurate estimates of electrical and magnetic field levels and energy densities. Power levels and field intensity levels derived from the models are required for test planning from the beginning, meaning that M&S is a continuing part of the test programme.

3.8.1.2.2 Laboratory Tests

Development of HPM systems and HPM test design may require iterations of analysis to quantify electromagnetic-field levels and repetitive effects testing. Multiple trials on specific electronics may result in an intensive investigation. For the ultra-wideband HPM weapon, multiple trials in the laboratory may be required to develop statistical estimates for the transient waveforms and repeatability of the output. These tests are best done at the laboratory level of development.

3.8.1.2.3 Ground Tests

In anechoic chambers or remote open-air ranges, HPM systems are measured and characterised. Effects data on targeted systems are collected and analysed. Adequate instrumentation is essential for performance measurements and also for safety. Instrumentation requirements must include measurements of transient fields from systems or sources by field sensors that often are made using B-dot or D-dot field sensors. Sometimes, these sensors may have to be placed inside equipment to properly characterise the effects at the physical level. Fast data acquisition equipment is required since some measurements may be required under the nanosecond timeframe.

3.8.1.2.4 Flight Tests

Flight tests will tend to be focused on system and mission compatibility. There is more emphasis on operational utility and target effects, although this may be difficult since the observable effect may be subtle. In addition to displayed information on the flight platform, instrumentation at, on, or in the target is required. Weather and other atmospheric parameters will be needed.

Unmanned HPM test platforms and target vehicles may require flight termination systems for safety. Those systems must be implemented such that they survive the HPM exposures and can still provide the safety functions required.

3.8.2 High Energy Laser Systems

HEL weapons direct light energy at targets using the properties of coherent electromagnetic radiation. The HEL systems are often categorised by the method of excitation, cooling, or the gain material. Some HELs are gas-dynamic lasers. These lasers are pumped by combustion or an energetic chemical reaction. Some lasers have a liquid gain medium or are liquid-cooled. Solid-State lasers (SSLs) have a crystalline or glass gain medium. SSLs have recently become viable contenders for HEL applications. Recent developments also include fibre-optic lasers and free-electron lasers. Fibre-optic laser development may result in easier handling and lower cost. HELs offer wavelength tunability. All lasers can be formed into a tight beam because of the property of coherence, meaning that the phase relationship is preserved to the point that interference of the waves can occur.

The best known HEL system is the YAL-1 Airborne Laser (ABL) shown in Figure 3-29. The ABL is a modified Boeing 747-400 designed to kill ballistic missiles in the boost phase. It autonomously detects, tracks, and engages ballistic missiles, and provides accurate missile launch location and impact points. [1]

Figure 3-29: The YAL-1 Airborne Laser System – (USAF Photo).

3.8.2.1 HEL System Components and Operation

Figure 3-30 illustrates the basic elements of an HEL-type system. Prime power can take different forms, such as chemical or electrical. The prime power provides energy to the pump mechanism. Lasers must have a pump to put energy into the gain medium such that a population-inversion of the laser energy states is created. Most lasers require an efficient cavity to support multiple passes of photons through the gain medium. Controls may be complex due to the requirement for beam steering and control, including precise pointing. Propagation includes not only attenuation effects, but optical effects from atmospheric turbulence, scattering, or a heterogeneous path. As a result, the beam control may include optics to compensate the beam for the atmospheric effects for longer-range systems.

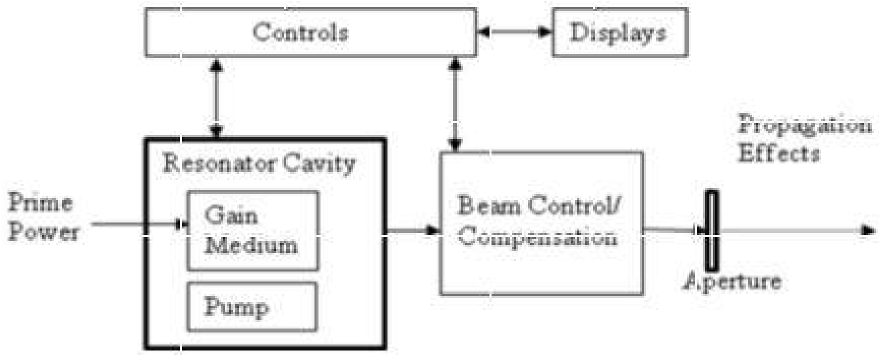


Figure 3-30: Simplified HEL Weapon/Source Block Diagram.

3.8.2.2 HEL Systems T&E

Testing of lasers will vary depending upon the physics phenomenon that produces coherent emission. These lasers have different test objectives based upon the unique properties of the medium and proposed effect. They will, however, have certain input and output characteristics and figures of merit that allow comparison and produce some commonality in weapons applications.

3.8.2.2.1 M&S

Because of the EM propagation phenomenon, M&S is an important part of design, testing and usage. Power levels and field intensity levels derived from the models are required for test planning from the beginning, meaning that M&S is a continuing part of the test programme. Because of the often specialised nature and unique designs for DE weapons, the testing will differ between systems. Some of the common T&E approaches for DE systems are discussed below.

3.8.2.2.2 Laboratory and Ground Tests

Laboratory testing of concepts and demonstrators is likely to be very technically complicated. Testing of sub-systems is likely to be extensive due to the complexity and the need for a build-up approach.

In the laboratory, key laser performance characteristics can be accurately measured and characterised. Output is usually measured by instrumentation that records multiple temperature measurements in a beam dump, converting it into a calorimeter.

Common laboratory and ground test performance measures include:

- Power;
- Brightness (in units of power per solid angle); and
- Delivered fluence (in joules per unit area).

The amount of fluence, or flow of energy, on a target is related to the beam quality. Beam quality is generally a ratio relationship between the total energy deposited to an ideal amount of energy, expected in a diffraction-limited system. There are several parameters used to describe beam quality, to include Strehl, M-squared, and power-in-the-bucket. Formulas and algorithms for predicting and calculating these from test data are found in textbooks and scientific publications.

Based on laboratory and ground test results, three operationally important measures can be determined:

- Probability of kill (P_k);
- Required dwell time in units of seconds; and
- Effective range, in miles or kilometres.

Some of the common data requirements involved in integrating a HEL into a flying platform are power consumption, charging timelines for the energy storage elements, heat dissipation, and the ability to focus the beam in the flight environment. For production versions of HEL systems on a flying platform, compatibility testing, EMI/EMC, EW, HPM susceptibility, and network-centric interoperability tests may be required. These tests are done more efficiently in the appropriate ground facilities, such as installed-equipment facilities and anechoic chambers than during flight tests. For the flight environment assessment, the beam focus estimates must account for the aerodynamic effects around any exit apertures.

3.8.2.2.3 Flight Tests

Early flight testing to reduce the risk of adding an HEL to an aircraft may be prudent. These tests may involve the aerodynamics changes for installing turrets, fairings, and windows. Early flights with sub-systems or surrogates may be used to verify heat removal and other form, fit, and functions of the interfaces to a laser pallet or system.

Final flight testing of HEL weapons will tend to be more operational-effect oriented. Targets may be used with various instrumentation schemes. A successful effect is likely to be a visible one that includes significant damage, as opposed to HPM where the effect is more subtle. Although the effect may be obvious from visual and infrared sensors and human observations, failures to achieve an effect may be much less clear. As a result, instrumentation on and around the target is required. Pointing and tracking may have to be assessed at lower power levels to avoid damage to sensitive detectors and data acquisition systems on the targets. To determine functions that predict P_k, target fluence levels will be required for each set of trials. Weather and other atmospheric parameters will be needed. Their effects on propagation must be modelled and verified.

Safety requirements for the test range may include monitoring the intended beam as well as inadvertent reflections or glint, to avoid inadvertent propagation to populated areas or other craft. Flight termination systems on targets must be implemented such that they either survive or avoid exposures and provide the safety functions required.

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Chapter 4 – T&E OF EP TECHNIQUES

4.1 INTRODUCTION

This chapter describes EP techniques and procedures. A general discussion of EP testing is presented and a simplified test example is presented to illustrate how the EW test process applies. Finally, EP through Emission Control (EMCON) and associated testing are discussed.

4.2 EP TECHNIQUES AND PROCEDURES

The EW division of EP differs from the ES and EA divisions in an important way. ES and EA usually employ dedicated systems to accomplish a specific purpose. EP techniques are normally incorporated into EW and non-EW systems as a means of protection from hostile EA. EP can also be procedural in nature such as employing Operational Security (OPSEC) measures, EMCON, and spectrum management.

All unprotected sensor systems, such as radar, are vulnerable to some form of EA. For example, an unprotected airborne interceptor's FCR would be vulnerable to a basic EA technique such as a Velocity Gate Pull-Off (VGPO). VGPO is an EA technique that attempts to deceive the FCR by stealing its velocity gate and injecting false target information into the FCR. A radar designer knowing that an adversary's EA will likely attempt to accomplish a VGPO will therefore incorporate logic, i.e., Anti-VGPO (AVGPO), into the FCR to recognise that a VGPO technique is being attempted and to negate it. Techniques such as AVGPO are often called ECCM. [1],[2] This also highlights the value of OPSEC and the need to protect information about potential vulnerabilities of friendly equipment from hostile interests. When hostile EA system developers design their systems they will use all known vulnerabilities to optimise their EA technique's effectiveness. If information about potential vulnerabilities is denied to them, they need to adopt more general techniques that are usually less effective than the ones designed to exploit specific vulnerabilities of the radar.

EP techniques tend to be the result of developments of EA capabilities. Most EP techniques are defined in relation to how they counter a specific EA threat. Usually, the EP technique is some improvement in the system design that counteracts the effect(s) of a specific EA technique; therefore, it is difficult to understand the purpose of a specific EP technique without knowing the EA technique that it is designed to counteract. This close relationship between EA and EP means that EP testers must plan, conduct, and evaluate testing based on a complete understanding of both the SUT and the threats that challenge it.

The EP test requirements most often encountered will involve ECCM of airborne radars. Figure 4-1 shows a block diagram of a generic airborne radar.

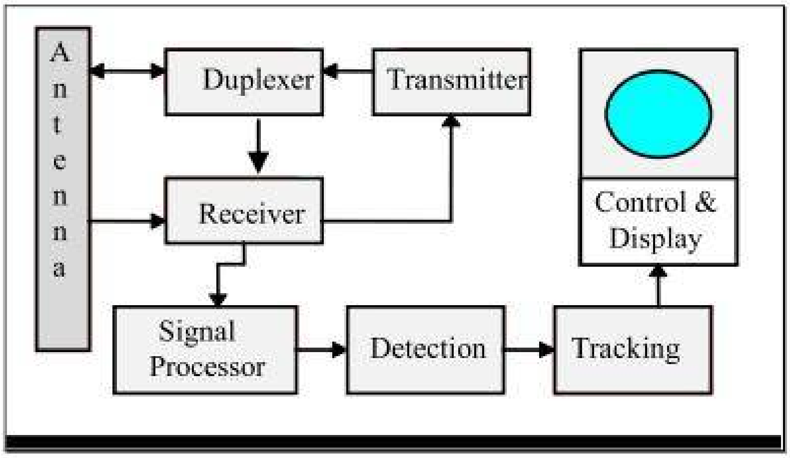

Figure 4-1: Generic Radar Block Diagram.

Each element of this radar is a potential victim of EA; therefore, some EP technique should be considered. The antenna's greatest vulnerability may be to stand-off jamming introduced through the sidelobes. The associated EP technique is to reduce sidelobes to the lowest possible level and, as is common nowadays, to equip the radar with a guard antenna which has an antenna pattern which covers the sidelobes. The radar can compare the jamming power from the two antennas and by that suppress signals introduced in the sidelobes. A similar relationship exists with the antenna's sensitivity to cross-polarised signals. If the antenna is designed for low cross-polarisation response, then it will be more robust against EA techniques that rely on jamming with cross-polarised signals.

The radar transmitter can protect against some EA techniques by having features such as frequency hopping, PRF stagger or jitter, pulse width modulation or compression, or other parametric diversity; a broad tuning range; or high transmit power. Each of these features is a valid EP technique and will require specific testing in order to characterise the radar transmitter's overall performance in a jamming environment.

Similarly, the radar receiver design can incorporate features to reduce its vulnerability to common EA techniques. High local oscillator and first Intermediate Frequency (IF) will result in increased image frequency rejection thus improving the receiver's ability to operate in a jamming scenario. Recent improvements in signal processing have led to major improvements in EP and pose significant new challenges for the EA designer. As digital signal processor components have increased in both speed and density, functions within radar signal processors have become more resistant to both deceptive and power-based EA techniques. Some features of signal processing found in modern airborne radars include programmability, high range and Doppler resolution, and signal processing reserve capability in both memory and computing resource timeline. Each of these features can result in important improvements to radar's EP capability. The primary objective of EP T&E is to characterise the radar's resistance to various EA techniques and assess its suitability for operation in an EW environment.

4.3 TESTING EP TECHNIQUES

The constant evolution of EP and EA provides some interesting challenges to the tester. As with EA, detailed knowledge of the threat is the tester's greatest resource. The following paragraphs describe how test resources can be applied at each level to evaluate the performance and effectiveness of the EP techniques.

4.3.1 Modelling and Simulation

Many EP techniques are based on complex and sensitive circuitry in the system being protected. As such, all elements of the EW test process should be considered in planning EP tests. M&S will be of particular value in both the test planning and evaluation portions of the test process. A digital model of the SUT can be used to analyse potential effects of jamming or other EA techniques. Antenna designs can be evaluated for their sidelobe characteristics that in turn will provide insight into the system's vulnerability to noise jamming introduced into the sidelobes.

The signal processing circuits of radar systems are excellent candidates for digital models. These models can be used both in the design of the signal processing circuits and as a tool to evaluate susceptibility to various jamming techniques. Current EW industry trends are to establish standards for models that permit a compliant digital model of a system in the design phase to be evaluated in the presence of previously established threat models. This approach permits both designers and testers to assess the behaviour of a new radar system with respect to various generic and specific EA techniques. Based on the results from this step in the test process, testers can determine those conditions most likely to reveal performance limitations or other problems in the SUT.

4.3.2 Ground Test

Various laboratory or ground facility tests will prove invaluable in developmental testing of EP functions. The majority of the EA techniques that may be overcome through some form of EP are based on the characteristics of EM waveforms, not on the dynamic properties of ships, land vehicles, aircraft, or missiles. Therefore, if the SUT, such as an airborne radar, is subjected to jamming signals while in a laboratory or spread-bench environment, the results observed will usually be indicative of the eventual installed system performance. Tests in SIL and HITL facilities will permit a large number of trials, with a high degree of repeatability at a low cost. Results from these tests can be quickly and easily compared with results from the digital M&S previously completed. Differences between the model results and those obtained in the SIL or HITL should be investigated and resolved. Appropriate updates to the models used are made before progressing to more expensive and complex test conditions.

One portion of nearly all EW and avionics systems that is particularly sensitive to installed performance is the antenna or sensor aperture. For the case of RF systems, antenna performance can be significantly altered due to installation effects such as other nearby antennas acting as parasitic oscillators or other parts of the aircraft causing blockages to the antenna pattern. Tests in ISTFs can efficiently lead to the evaluation of such effects. Not all ISTFs can support the actual radiation of RF signals required for measurement of antenna system performance. The tester must always be careful to select facilities in each test category that can support the specific types of tests deemed necessary for the system of interest. For instance, if the installed performance of the antenna systems is well known but a concern exists about the integration of new signal processing circuits with other elements of an aircraft's avionics, then operation in an ISTF that permits free-space radiation of RF signals may not be necessary. A smaller facility with lesser anechoic properties will suffice. If, on the other hand, the SUT has an uncharacterised antenna system and must operate in a complex radiated electromagnetic environment, then the test team should consider using an ISTF with broad anechoic properties and a wide-operating frequency range.

4.3.3 Flight Test

Flight testing is usually the final step and should hold little potential for surprise if the previously described steps are carried out. However, it is possible that some aero-mechanical effects not simulated in the earlier stages will cause problems. Movement of antennas due to flutter or aeroelasticity effects can result in erroneous Direction Finding (DF), ranging, or velocity determinations.

4.4 ECCM TEST ILLUSTRATION

The following example illustrates the test process for a notional airborne FCR with an EP technique designed to mitigate the effects of sidelobe jamming. Assume for this example:

- SUT is an Airborne Interceptor (AI) radar.
- A digital model of the radar and threat jammers exists.
- Radar antenna pattern has been previously characterised in both azimuth and elevation.
- Radar's primary EP technique to negate effects of barrage noise jamming is sidelobe cancellation.
- For HITLs and ISTFs, a threat jammer simulator is available with adjustable power output.

4.4.1 Test Objectives

During test planning meetings the military end user, the radar manufacturer, PSI and testers determine that the military end user is particularly interested in how the radar system will perform in the presence of SOJ barrage noise jamming. Barrage noise is an EA technique that produces broadband noise energy to mask the reflected energy from a radar. When applied by an SOJ, the noise is introduced into the radar sidelobes to mask returns that are occurring in the main beam. The success of barrage noise jamming is primarily a function of J/S. These factors will help to determine appropriate test objectives, plan test activities, and determine the data requirements to support an evaluation. The first step is to determine the test objective. There will be one simple test objective in this example to demonstrate the process. The test objective is: Determine the minimum jamming power required to obtain the specified J/S at the input to the radar receiver at various azimuth angles between 10 and 45 degrees off the nose of the test aircraft.

4.4.2 Pre-Test Analysis

A key to effective testing is to develop an understanding of the SUT, its intended operating environment, and the strengths and weaknesses of the threats it will encounter. Developing this understanding is the first element of pre-test analysis. As shown in Figure 4-2, there are two areas of interest defined, a 35-degree sector on the left and a 35-degree sector on the right. The jamming signal must be within the bandwidth of the radar receiver to be effective. The antenna pattern for the radar antenna will be an important consideration in determining the angular resolution for testing. For this example, it is assumed that the antenna pattern is of adequate consistency to permit measurements to be taken at 5-degree increments. The initial characterisation of the antenna pattern would have been accomplished in a measurement facility specialising in RF antenna measurements.

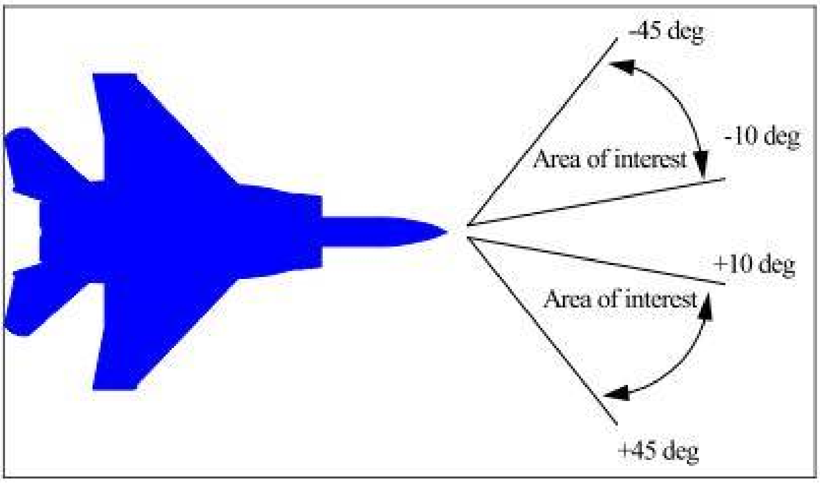

Figure 4-2: Areas of Interest.

The EP technique used in the example radar is sidelobe cancellation. This technique utilises auxiliary antenna elements to receive the jamming signal, determine its effect, and cancel that effect in the main antenna channel. In order to evaluate the effectiveness of the sidelobe canceller, the test will be conducted with and without the EP technique enabled. Since the radar antenna is a critical element in the vulnerability of the radar to stand-off jamming, all tests will be conducted with RF radiation through the antenna.

The pre-test analysis we must define the test concept, determine test points, predict outcomes, establish analytical processes that will be applied, and decide what data must be acquired. Since there is a digital model of both the SUT and the SOJ, these tools can be used to determine if there are critical angles or frequencies at which the jamming will be particularly effective, or the EP technique is particularly ineffective. The model will also be helpful in determining what data need to be collected and the requirements for range, resolution, and accuracy of that data.

4.4.3 Test Execution

The next step is to execute the test. This step will be repeated several times, using various test resource categories as the confidence in the SUT increases. The results obtained will be compared to those predicted during the pre-test analysis after each iteration. The results will be used to correct or revise the models and to resolve differences between actual and predicted results.

4.4.3.1 HITL Testing

The first tests will be accomplished in a HITL with the SUT in a 'spread bench' configuration permitting easy access to test points with generic laboratory test equipment such as spectrum analysers and oscilloscopes. The radar antenna, auxiliary antennas, and the jammer simulator transmit antenna will be located in a small anechoic chamber where RF radiation can be accommodated with adjustable power levels. During this testing precise measurements can be made of the actual power levels and J/S ratio at each point of interest in the antenna pattern. Data can be either hand recorded or automatically logged by the test facilities instrumentation support system.

4.4.3.2 ISTF Testing

Testing the radar in its installed configuration under precisely controlled conditions can be accomplished in an ISTF. This will be an important test since it will be the first opportunity to measure the system performance with installation effects accounted for. Both facility and aircraft instrumentation systems should be utilised during this phase of testing. It will provide a correlation between the test aircraft instrumentation system that will be used during flight test and the facility instrumentation that is the primary data acquisition source during the ISTF tests. Large amounts of data can be easily collected in this environment with a high degree of repeatability. These data will form the basis for an accurate statistical baseline of system performance. Both HITL and ISTF testing support a tightly controlled RF environment where only the signals of interest are present. This will not be the case in flight test.

4.4.3.3 Flight Test

The final phase of the test project will be conducted in flight on an OAR. Three aircraft will be used. The first aircraft will simulate the actions of an adversarial SOJ aircraft. The second aircraft will represent a threat target aircraft. The third aircraft, the test aircraft, will carry the SUT and be instrumented to provide either onboard recording or telemetry of critical parameters needed for evaluation of the SUT. Time Space Positioning Information (TSPI) for all three aircraft is required. These data will be used during post test analysis to determine the exact position of the jammer and target with respect to the SUT radar antenna.

Flight profiles for all three aircraft will be established to maintain the jammer aircraft within the 35-degree sector on either the left or right side of the test aircraft. During this phase of testing the test objective is modified to provide a more operational focus. The objective is now redefined as: *Determine the minimum jamming power required to defeat the radar's ability to detect, track, and display a one-square-meter target with stand-off jamming at various azimuth angles between 10 and 45 degrees off the nose of the test aircraft.* This revised objective creates a number of new requirements. The objective describes a target aircraft with a RCS of one square metre. While the aircraft available to serve as a target may not directly meet this requirement, data obtained during testing can be corrected for any difference in the RCS. This does, however, require high accuracy and resolution TSPI capability on the open-air range. Also, the primary indicator of jamming effectiveness will now be the pilot of the test aircraft. When the jamming is sufficient to obscure the target on the pilot's display, then we will consider that the EP technique is ineffective. While the precise data gathered during the previous phases of testing are necessary to efficiently develop and improve the SUT, these operational data will ultimately determine whether or not the system will be acquired and fielded.

4.4.4 Evaluation

The system manufacturer, PSI and the military end user may have different views of what the results mean; the manufacturer may use the results of testing to demonstrate that all specifications have been satisfied, while the military end user may determine that based on test results, the system will not satisfy the operational requirements. Due to the differences in interpretation of test results and the potential economic and operational impacts associated with these interpretations, evaluation is one of the most critical and controversial elements of the test process. To the greatest extent possible, all parties involved in the development and test of a system reach agreement prior to the start of testing as to what data will be used in the evaluation, and what calculations and statistics will be applied to the data. Finally, everyone must reach agreement as to exactly what constitutes success or failure.

For the example test the problem was bounded to some degree in the test objectives' statement. For the flight test objective, only data acquired when the jamming aircraft is within the 10 to 45-degree sector on either side of the test aircraft will be used. The evaluation of the test results will generally be communicated through an interim or final report. This report should clearly state any constraints or limitations on the testing, what was observed, what was concluded from those observations, and any recommendations resulting from those conclusions. If, based on the evaluation, the decision makers can verify that any operational risks associated with fielding the system are acceptable, and that user needs are adequately satisfied, then testing can be declared complete. If the evaluation leads to a conclusion that the SUT requires additional improvement prior to acceptance or fielding, then another cycle of the test process will occur.

4.5 EP THROUGH EMISSIONS CONTROL CAPABILITIES

In addition to the ECCM techniques discussed above, there are passive approaches to EP. One of the most significant is EMCON. EMCON addresses both intentional and unintentional emissions.

4.5.1 EMCON Concepts

The most direct means of limiting an adversary's ability to apply EA techniques is by rigid control of friendly EMCON. As a simple example of this process, consider an ARM targeted at a friendly radar site. Since the ARM homes in on the RF radiation from the radar, it will lose that guidance if the radar transmissions are ceased. The planned cessation of the radar emissions would be considered a form of EMCON and would clearly be an effective method of EP.

IADS typically contain passive RF sensors to detect and track hostile aircraft. These sensors can track both intentional and unintentional RF radiation coming from the air vehicle. An air vehicle should have an RF management system to control all onboard RF transmissions. Unnecessary emissions should be eliminated and in the event that they cannot be eliminated they should be characterised so that their effects can be procedurally mitigated.

4.5.2 Testing for Unintentional Emissions and EMCON Capabilities

Virtually all electrical and electronic components on an aircraft have the potential to radiate or re-radiate RF energy, which may be detected and intercepted by an adversary. While some of these potential emissions can be observed during early phases of development, it is most often the case that they are discovered after all systems are installed and integration in the host platform has begun. As a result, ISTFs are frequently used to characterise these unintended emissions.

4.5.2.1 Ground Tests

Large anechoic chambers are most useful in conducting tests to determine the exact nature and source of all signals radiated from an aircraft during operation. One approach frequently used is to establish a matrix of all possible switch combinations and then step through each configuration while using a calibrated, high sensitivity receiver to sweep through the entire range of frequencies to be evaluated. If energy is detected with a particular combination of aircraft equipment energised, then engineers can isolate the exact source. At this point both the user and designer must determine what action is to be taken to either reduce the emission or accept the condition.

While this type of testing is time consuming and requires specialised facilities and equipment, it has proven to be the most efficient manner to locate specific sources of unintentional emissions. Of course, intentional emissions can also be used to detect, locate, and engage an aircraft and must also be characterised. Again, the anechoic chamber is an efficient and cost effective location for this task.

4.5.2.2 Flight Tests

The results from ISTF tests can be used along with digital models of threat systems to determine an aircraft's susceptibility to such threats. In many cases actual flight test against simulated threats and

RF measurement systems can be employed to evaluate susceptibility. While determination of the exact source of the offending radiation may be difficult or impossible in an OAR environment, flight tests do provide the most realistic conditions. It is not unusual to regress to ISTF testing after the first round or two of flight testing. This iterative approach will generally converge on the best balance of emissions reduction and operational utility. Operational tests and some developmental tests on an OAR are accomplished using operationally representative flight profiles against typical threat laydowns. Through careful manipulation of the flight profile relative to the threat simulator placements, specific conditions thought likely to occur in actual combat can be evaluated. The analysis of system performance during such testing provides the best overall assessment of military worth.

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Chapter 5 – T&E ASPECTS OF EW SYSTEM ARCHITECTURE

5.1 INTRODUCTION

The approach to testing any specific EW system or function depends on its architecture. Testing and the subsequent evaluation of standalone systems are relatively straightforward. When the EW system is combined with other systems and sub-systems on a single platform, both the quantity and nature of interactions which must be considered grow substantially. This chapter focuses on testing federations of equipment and systems, and integrated systems.

The even more complex case of Multi-Platform Geo-Location using RWR/ESM as a threat Emitter Location System (ELS) is not explicitly covered in this Handbook. Many of the considerations are similar to the single platform integrated EW system, but with the added complication of data links between the platforms concerned. Other information is available to the interested reader. [1]

5.2 STANDALONE EW SYSTEMS

The simplest category of EW systems, from a T&E point of view, are those having minimal interaction with other systems on the same platform. These standalone systems can usually be evaluated without a rigorous evaluation of the performance of other aircraft functions. Of course, interoperability and EMI issues must be considered for standalone systems.

5.2.1 Standalone System Description

Standalone EW systems are those systems that do not depend on data, information, cueing, or other functions from other EW or avionics systems on the platform. These systems generally have a specific single function such as radar warning, jamming, or chaff dispensing. Standalone system testing is relatively simple; the system is exposed to the expected threat environment and observed for the correct response.

5.2.2 Standalone System Testing

A standalone RWR is designed to provide the pilot with visual and audio warnings when the aircraft is illuminated by one or more threat radar systems. As discussed in Chapter 2, specific tests are performed in both ground and flight environments to measure and establish the performance of each major functional element of the RWR. The antennas are characterised individually and in their installed configuration to verify their frequency, spatial coverage and gain performance. Receiver tests are conducted to determine sensitivity, selectivity, and other key parameters. The signal processing function is tested to ensure that all threat signals specified for the system are properly categorised. Finally, the Man-Machine Interfaces (MMIs) are evaluated for correct operation. While this overall process may require hundreds of individual tests, the evaluation of results remains relatively simple and the test conditions can be easily achieved. Each element of the system either functions as specified, or not; each test condition is discrete and has little or no dependence on other test conditions.

5.3 FEDERATED EW SYSTEMS

Federated systems represent present an increased level of complexity. Additional interfaces have to be considered in the design of the test program. A depiction of this architecture is shown in Figure 5-1.

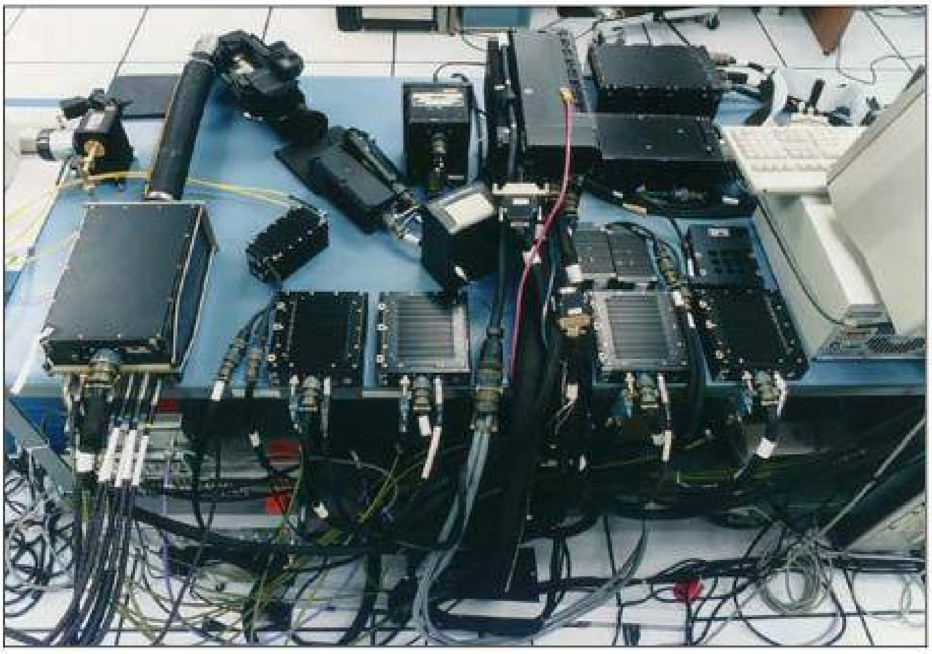

Figure 5-1: Federated System in HITL Test at ECSEL Facility, Pt. Mugu, California.

5.3.1 Federated System Description

Federated systems are those systems which maintain their own functional identities or boundaries, but are dependent on data, information, cueing, or other functions from other systems outside of those boundaries. Most avionics and EW systems of the late 1970s through the early 1990s have exhibited this characteristic.

The testing of such systems is considerably more complex than the standalone case previously discussed. The causes of this complexity are best understood by reviewing an example test process for a federated RWR and RF jamming system. Generally, such systems still have their own control panel and displays.

5.3.2 Federated System Testing

For this example, consider that the RWR and jammer are installed on the same platform and designed to work against the same set of threats. They share a common threat database or MDF. When the RWR detects a threat it will be displayed on either a dedicated system display or on a MFD in the cockpit. The display will show a unique symbol representing the threat type, azimuth, and estimated lethality. The pilot also receives a warning tone in his headset. Upon command from the pilot, the threat identification and location data are passed to the jammer sub-system. The jammer determines the optimum jamming response for the detected threat, tunes a receiver to the proper frequency, and emits the necessary RF energy. If the jamming is effective, the RWR will detect that the radar is no longer tracking the aircraft. From this scenario the example test program can begin to be structured, the test resource requirements determined, and an evaluation process planned.

Two common MOPs for the example system are:

- Response time for the RWR to detect each threat signal in the MDF.
- Response time to initiate the optimum jamming waveform.

Many other MOPs apply to this type of testing, but these two serve to illustrate the point. While the first MOP appears to focus on the RWR standalone performance, there is a potential for interaction with the jammer through the MDF. If both the jammer and the RWR attempt to access the MDF simultaneously, there may be a delay in the data needed by the RWR. Consequently, testing must be structured to acquire data under various operating conditions for both the RWR and the jammer. The data collected must be categorised to reflect the operating conditions to determine if there is a significant delay imposed by multiple systems sharing a common MDF. The system specification requirement identifies how much delay acceptable. Certainly, the standalone performance of the RWR will be a dominant factor in this objective, but additional testing to ascertain the overall performance of the federated system is of paramount importance to the military end user.

The second MOP clearly implies evaluation of the fully federated system. The RWR, jammer, shared MDF, displays, and the pilot all play an important role in overall system performance and effectiveness. To fully analyse and evaluate the results of this test, insight into the performance of each individual component of the system is necessary. The evaluation should not just assess if improvements are needed, but if so, which part of the system is the best candidate for improvement. This MOP also brings into play the human operator; a component with a high degree of variability. In order to appreciate the operator's effect on overall system performance, data will need to be collected under a wide range of operational conditions, and with a range of operators.

All of this leads to the conclusion that test of federated systems brings about an increased burden on the test planning and analysis processes over that of the standalone systems test. The same facilities will be used, but the number of test runs or flights may increase significantly as the system complexity grows.

5.4 INTEGRATED EW SYSTEMS

Some combat aircraft designs from the late 1990s onward have moved from the relatively simple federated approach to an extensive integration of EW and avionics functions. The U.S. Air Force F-22, shown in Figure 5-2, is an example of this integrated approach. Functional integration offers numerous advantages to system designers while creating complex challenges to testers.

Figure 5-2: F-22 Employs a Fully Integrated Avionics and EW Suite – (USAF Photo).

The Eurofighter Typhoon also has an integrated DAS, comprising EuroDASS 'Praetorian' (ESM-ECM, TRD, MWS and LWS), as shown in Figure 5-3, Defensive Aids Computer, and flare and chaff dispensers.

Figure 5-3: Praetorian Components – (© SELEX Galileo 2008).

5.4.1 Integrated System Description

Integrated EW systems are not just a combination of standalone systems linked together as is the case with the federated approach. Rather, integrated systems tend to have a homogeneous functional identity. There is no discernible boundary between sub-functions such as radar warning, missile warning, jamming, or other EW activities. Most, if not all, components in the system may be shared between the sub-functions on the basis of complex scheduling and resource control algorithms.

Modern highly integrated systems employ a number of apertures, e.g., antennas and IR detectors, to perform a variety of functions. EW and non-EW system designers no longer necessarily treat these apertures as dedicated to a single sub-system. An antenna on a modern fighter aircraft FCR will generally be a high-gain, electronically steered, phased array that can be tasked to support sensing functions for other onboard systems.

5.4.2 Testing Integrated EW Systems

Testing of isolated functionality becomes difficult, if not impossible, with the operational software[1] in place. Flight tests will reveal little of the source of performance problems with integrated systems. ISTF and HITL test facilities that can make large numbers of test runs with precisely controlled conditions and extensive instrumentation are essential to the T&E of integrated systems.

The OAR remains useful in establishing the overall effectiveness of integrated EW systems, as discussed in Section 6.8. However, in order to evaluate the system effectiveness in conditions outside that which can be demonstrated with OAR resources, the tester must rely on digital M&S and ground-based resources. The current trend is to combine digital models with hardware threat and environment simulations to provide controllable, repeatable stimulation of the entire test aircraft in an ISTF.

This capability to immerse the entire aircraft in a controlled and representative EW environment requires that all signals of interest (RF, IR, UV) be simultaneously generated in a coherent manner. Information content must be consistent among and between emissions from both the SUT and the simulated environment. All objects used in the test scenario must appear to exist at the right time and place; that is, coherency must exist in all domains detectable by the SUT.

These requirements drive ISTF signal and scene generation and scenario control software to the far extreme of current technical capability. A simple example serves to help understand this demand on test resources. Assume the integrated EW system being tested can sense RF and IR emissions from a potential threat aircraft and correlate this sensor data with its own radar detections and tracks. The test facility will then be required to generate a radar return representative of the threat aircraft's RCS, an IR scene, and other RF emissions all coming from the intended target position. Looking at this requirement in the time domain, all simulations must present realistic target motion and the resulting changes in physical characteristics of each signal. Radar target returns must be modulated with the correct Doppler, scintillation, and other characteristics to permit a viable test of a coherent processing AI radar.

If, due to minor time or space positioning errors in the simulation, the IR emissions from the target were displaced from the radar target simulation, then the SUT may declare two targets rather than one. Clearly, the eventual outcome of a one-versus-one engagement should be different than a one-versus-two engagement. This difference would invalidate the planned test.

For ISTF testing of modern integrated EW systems, this simple example must be replicated many times to represent realistic threat densities. Very sophisticated and costly threat and signal generation systems, scenario control software, digital models, and instrumentation are needed to accomplish these high-

[1] Operational software in this usage means the OFP and the MDF. The terminology varies with Nations and services.

density, high-fidelity simulations. However, in spite of the cost and complexity involved, such test capabilities can pay great dividends in understanding the behaviour of integrated EW systems and isolating hardware and software failures, prior to flight test and combat use.

5.5 REFERENCES

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5.6 FURTHER READING

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Chapter 6 – EW T&E RESOURCES AND FACILITIES

6.1 INTRODUCTION

This chapter provides generic descriptions of ground and flight test resources and facilities commonly utilised in the T&E of EW systems and components. EW T&E capability types are introduced and their primary functional categories explained. Distinguishing factors of facilities are discussed. The chapter concludes with a section on the common use of many of the test facility types for EMC and EMI testing of EW and other systems.

Descriptions of known EW and related test facilities in NATO Nations are given in Annex A. Whilst this annex does not fully describe every resource that a project may wish to utilise, it represents a valuable resource for understanding the range of facilities available to meet the goals of a structured test process.

6.2 SCOPE OF EW T&E CAPABILITIES

A number of T&E facilities and resources, or 'capabilities,' are required to support:

- EW system design, development and performance verification against its specification;
- Government acquisition agency ('customer') and military end user acceptance; and
- Operational use of the platform.

There are various definitions of T&E capabilities across NATO Nations and these are typical:

- 'A Test and Evaluation (T&E) capability is a combination of facilities, equipment, people, skills and methods, which enable the demonstration, measurement and analysis of the performance of a system and the assessment of the results.' [1]
- 'The people, assets and processes to undertake evaluation with sufficient accuracy and timeliness to assure provision of through-life military capability.' [2]

Throughout this Handbook the human aspect of EW T&E capabilities is considered to be implicit. The operation of many of the facilities described in this chapter depends upon a high degree of specialist engineering knowledge and expertise in the Electromagnetics and Systems Engineering domains.

Facilities and equipment are described with reference to terminology used in the first issue of this Handbook and [3], with commentary and examples. The range of facilities is shown in Figure 1-6 and a non-exhaustive list of strengths and limitations of each is given elsewhere. [3]

Test capabilities are frequently categorised by their primary function, as given below:

- Modelling and Simulation (M&S);
- Measurement Facilities (MF);
- System Integration Laboratories (SIL);
- Hardware-In-The-Loop facilities (HITL);
- Installed Systems Test Facilities (ISTF); and
- Open Air Range (OAR).

In many cases, however, these definitions are overly and inappropriately restrictive. For example, large anechoic chambers are generally classified as ISTFs and yet they often provide excellent support in the role of MFs. The following sections explain the role of each of the above categories but are not meant to imply that facilities otherwise defined should not be utilised in a role outside their primary designation.

Test missions by location are summarised in Table 6-1.

Table 6-1: Test Missions by Facility Type.

Test Location	Primary Test Mission
SIL/HITL (Digital, RF and Intermediate Frequency)	R&D and concept development. Note: Often need simulation capability enhancement to be able to develop new or 'next generation' EW receiver systems/upgrades
	Requirements definition and system performance modelling
	HITL: Equipment/sub-system development and qualification
	Uninstalled sub-system performance verification (usually over full range of performance)
	Integration with other platform avionics; further development and sub-system performance verification, conducted in SIL
	ESM-ECM performance optimisation vs. specified threat environment
	Evaluation of new/upgraded threats and countermeasures development
	Development, evaluation and clearance of EW upgrades
ISTF (Anechoic Chamber and Other)	Platform-system integration. Further sub-system and avionics system development
	Installed system performance verification, including SUT irradiation with 'war mode' and other signals now allowed to be transmitted in the open air
	Fault/anomaly investigation, isolation and solution confirmation
	Airframe-systems aspects of EW upgrades' development, evaluation and clearance
Open Air Test Site	Free space, far field, illumination of aircraft-installed SUTs for cases where anechoic chamber tests not viable or unacceptably limited, e.g., antenna polar diagrams and ESM/ECM beam-forming measurements (far-field)
	Whole platform EMC tests
	Platform radar cross-section measurements
OAR and Other Flight Test Facilities	Residual installed performance verification tests for aspects not acceptably testable using above locations and methods
	Development and performance verification of aspects not ground-testable, e.g., combinations of tactics, flare/chaff dispensing, on-board RF jamming and towed RF decoys
	Evaluation/optimisation of EW system man-machine interface under flight conditions
In-Service Support – a.k.a. 'Sustainment' (Laboratories and OARs)	Mission Data Validation prior to and during training, operational evaluation and combat
	EW hardware/firmware and algorithmic software performance optimisation
	Post-maintenance and pre-flight check-out
	Evaluation and resolution of operational problems
	EW and countermeasures/tactics effectiveness evaluation/optimisation
	Mission rehearsal and aircrew/operator/maintainer training

An important distinction, especially relevant to RF EW systems, is the difference between 'un-installed' and 'installed' sensor and system performance. In the former case the sensor is not mounted on the platform, e.g., a stand-alone RWR antenna. In the latter case the sensor is mounted correctly on the platform, i.e., for the above example the RWR antenna would be mounted in a RAM-lined cavity in a fin-tip pod and covered by a radome made of dielectric material. The EM performance difference between the two cases can be large, in particular where the airframe is non-metallic (e.g., Carbon Fibre Composite), and this can result in system-level performance that requires modification to successfully meet the system's specification. Such modification can be expensive and time-consuming if not detected until the flight test and production phases. This risk can be adequately managed via validated modelling of installed performance of RF sensors, a topic mentioned in the next section 'Modelling and Simulation'.

6.3 MODELLING AND SIMULATION

M&S, which is also known as Modelling, Simulation and Synthetic Environments (MS&SE), is used to:

- Demonstrate system performance for aspects too complex or too expensive to verify by testing.
- Estimate error bounds where test repeatability is difficult or where tests alone would yield unacceptable error bounds.
- Supplement testing by interpolation between sparse data points or to extrapolate from measured data.
- Prove design concepts prior to final testing.

Most M&S undertaken as part of the design verification process is currently performed by equipment suppliers, who provide outcomes as acceptance evidence to the PSI. An area of promise is Computational EM Modelling (CEM), where modern computing power and innovative codes offer useful design optimisation and risk reduction for RF antenna installations on platforms. Table 6-2 indicates typical example M&S tools used in EW Design and Development (D&D) and T&E.

Table 6-2: Typical M&S Tools Applicable to EW D&D and T&E.

MODELS (Examples)		MODELLING LEVEL	TYPICAL MOEs	TYPICAL MOPs	VALIDATION
THUNDER	REFINEMENT OF MODELLING ASSUMPTIONS	Campaign	Campaign length	Aircraft availability	Wartime experience
EADSIM		Mission	Attrition levels	Number of encounters	Wartime experience
AWSEM, SAMOCLES		Engagement	Pk reduction factor	Miss distance	Trials data, including live fire
CEESIM/EGA		System	Jam-to-signal requirements, installed sensor coverage	Pulse characteristics, RF communications link success probability	Experimental data, including whole aircraft test
TLM, GTD/UTD		Sub-system and equipment	Impulse response, uninstalled antenna patterns	Circuit voltages, antenna gain, impedance, RF currents and voltages	Above + EM theory, physics textbooks, standard problems, other validated codes

Notable issues with M&S as relevant to EW T&E are:

- Simulation fidelity and model validation, i.e., how faithfully they represent real threats and EW equipments and their performance.
- Modelling of EW antennas, systems and intra-platform cabling is not sufficiently robust to maximise contribution to acceptance.

There is a continuing US and European thrust to move EW T&E toward ground test and M&S. This work, which requires extensive scenario modelling and the increasing use of EW equipment models, offers great promise in reducing not only the expensive flight testing phase, but also overall EW system development and Mission Data validation timescales and costs. There remains, however, doubt that some aspects, e.g., RF and IR jamming and other countermeasure effectiveness, will ever be fully cleared by M&S alone, i.e., without some residual element of flight trials. This is particularly true of simulations involving a 'man in the loop.' While M&S has become quite good at modelling phenomenology, it doesn't generally handle humans very well.

The topic of M&S, as applied to EW T&E, is expanded in Chapter 7.

6.4 MEASUREMENT FACILITIES

MFs establish the character of an EW-related system/sub-system or technology. They provide:

- EW and platform antenna pattern descriptions and platform signature data critical for system design and refinement, computer simulation, and EW equipment/system testing in HITLs, SILs and ISTFs.
- Capabilities to explore and evaluate advanced technologies such as those involved with various sensors and multi-spectral signature reduction. These are used to provide data that cannot be modelled adequately. In some cases, for example antenna pattern measurement, they provide data for validation of M&S used in the Verification and Validation (V&V) process.

Measurement facilities generally fall into the sub-categories:

- Antenna characterisation.
- Signatures measurement: RCS, IR, UV, and laser.
- EMC and EMI, on open air test sites and in anechoic chambers.

Platform-level examples of MF types are given in Figure 6-1.

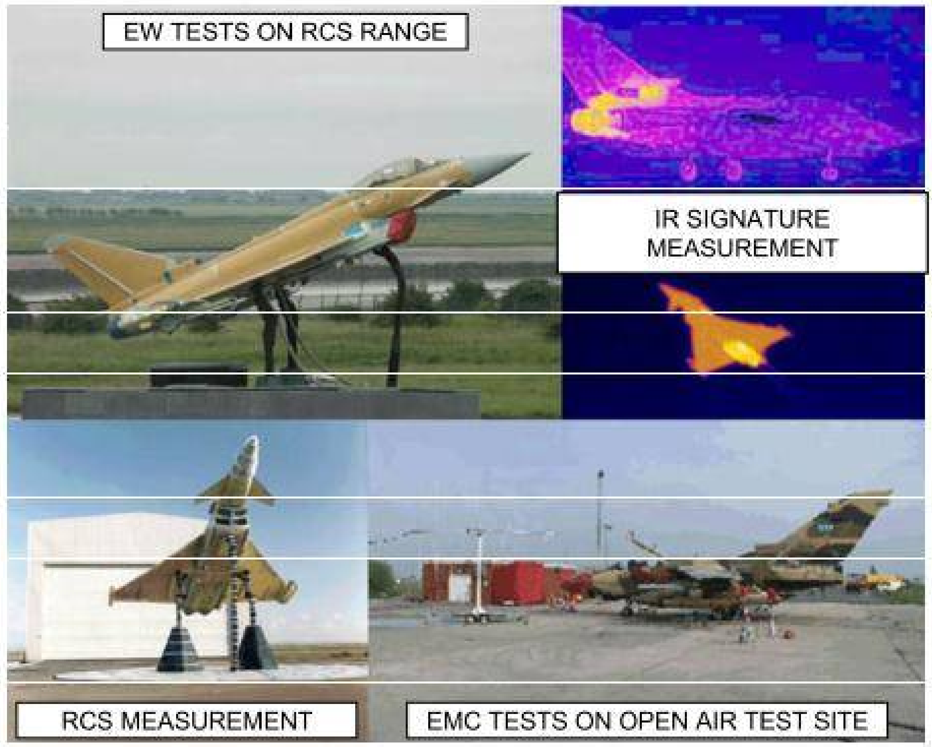

Figure 6-1: Measurement Facility Examples – (© BAE SYSTEMS 2010, All Rights Reserved).

6.5 SYSTEM INTEGRATION LABORATORIES

SILs are facilities designed to test the performance and compatibility of components, sub-systems, and systems when integrated with other systems or functions. They are used to evaluate individual hardware and software interactions and, at times, involve the entire weapon system avionics suite. A variety of computer simulations and test equipment are used to generate scenarios and environments to test for functional performance, reliability and safety. SILs are generally weapon system specific and are found in contractor (EW equipment supplier and platform/systems integrator) and Government facilities.

SILs often employ a variety of real-time/near-real-time digital models and computer simulations to generate scenarios and multi-spectral backgrounds. These models are interfaced with brassboard, prototype or actual SUT production hardware and software. SILs are used from the beginning of an EW system's development through avionics integration and fielding. Moreover, SILs continue to be used throughout an EW system's operational life to support:

- Investigation and resolution of in-service problems; and
- Testing of hardware and software modifications and updates.

Whilst the term 'SIL' is US-originated, equivalents in the UK and elsewhere are:

- Sub-System (SS) Rig, where individual EW equipments are integrated into a sub-system and developed prior to integration with other platform avionics.
- Avionic Integration (AI) or System Integration (SI) Rig, where – prior to release for aircraft use:
  - The EW sub-system is integrated with the rest of the platform's avionics and other systems; and
  - Those tests of EW sub-system performance required to be conducted by the project's qualification and verification test plan are executed.

Conventional SILs and SS rigs are usually found at the facilities of EW and DAS equipment supplier's and Platform and Systems Integrators. AI and SI Rigs are located at Platform and Systems Integrator facilities and, as they mostly have real avionic equipment fitted, are in fact hybrids of the generic SIL and HITL facility categories. EW testing performed in SILs and on SS/AI/SI rigs generally utilise EW/DAS equipments in a laboratory environment on a 'spread bench,' as in Figure 6-2, with all other aircraft data supplied via simulations generated by an external control computer. These computers often serve as master test controllers and also provide non-RF data acquisition and analysis, e.g., of data bus traffic.

Figure 6-2: EW Equipment on Avionics Integration Rig – (© BAE SYSTEMS 2010, All Rights Reserved).

EW Receiver stimulation is performed by RF threat emitter simulators such as the widely used Combat EM Environment Simulator (CEESIM). Characterisation of signals at RF can be executed by the use of various test equipments, e.g., spectrum and pulse domain analysers. However, for optimum measurement, recording and analysis of complex RF jamming waveforms from modern EA systems, EW T&E equipment such as the Signal Measurement System (SMS) is required. CEESIM and SMS[1], which are shown in Figure 6-3, are but one example of this high performance EW T&E equipment.

[1] CEESIM and SMS are products of Northrop Grumman, Amherst Systems Inc.

Figure 6-3: RF Threat Emitter Simulator and EA/ECM Signal Measurement System – (BAE SYSTEMS Photograph).

Once the DAS has reached suitable maturity it is integrated with other sub-systems, e.g., Displays and Controls, on an avionic integration rig. System-level performance verification testing is conducted using the EW equipments once integrated with the other real aircraft equipment on the rig. Once again EW receiver stimulation is performed by a threat simulator but the level of testing is reduced as most of the individual equipment and sub-system performance has already been proven by the earlier verification and qualification phases at the platform/systems integrator and equipment supplier.

All verification tests conducted on these rigs is traceable back to the original customer requirement through the Verification and Validation Requirements Matrix. Integration rigs are continually utilised throughout the platform's life to prove software and hardware changes and to re-test system fixes prior to release to the aircraft or to the customer.

6.6 HARDWARE-IN-THE-LOOP FACILITIES

HITL facilities are ground-based test facilities that provide a controlled and usually secure environment to test EW techniques and hardware against real or simulated threat systems.

- Primary EW HITL facilities contain simulations of hostile weapon system hardware or the actual hostile weapon system hardware. They are used to determine threat system susceptibility and for evaluating the performance and effectiveness of EW systems and countermeasure techniques.
- Some EW HITL facilities contain friendly weapon system hardware. They are used to evaluate and improve the performance of friendly weapon systems in the presence of various hostile and friendly EW activities. These HITL facilities can also be used to test EW systems where the friendly weapon system represents a potential threat technology.

Although SS, AI and SI rigs include, by definition, real hardware-in-the-loop, generally understood HITL facilities are secure (usually screened or anechoic) indoor facilities that enable un-installed testing of EW techniques against simulation of threats or real threat hardware. Whereas sub-system and avionic integration rigs generally do open-loop EW testing, primary HITL facilities have the capability to do closed-loop testing, where own EW system effectiveness can be assessed and optimised against threat system sensor systems, and the EP of own EW systems and sensors can be assessed against hostile jamming equipment.

Examples of HITLs are shown in Figure 6-4 and Figure 6-5.

Figure 6-4: EW HITL Facility Example (1): US Navy EC Systems Evaluation Laboratory.

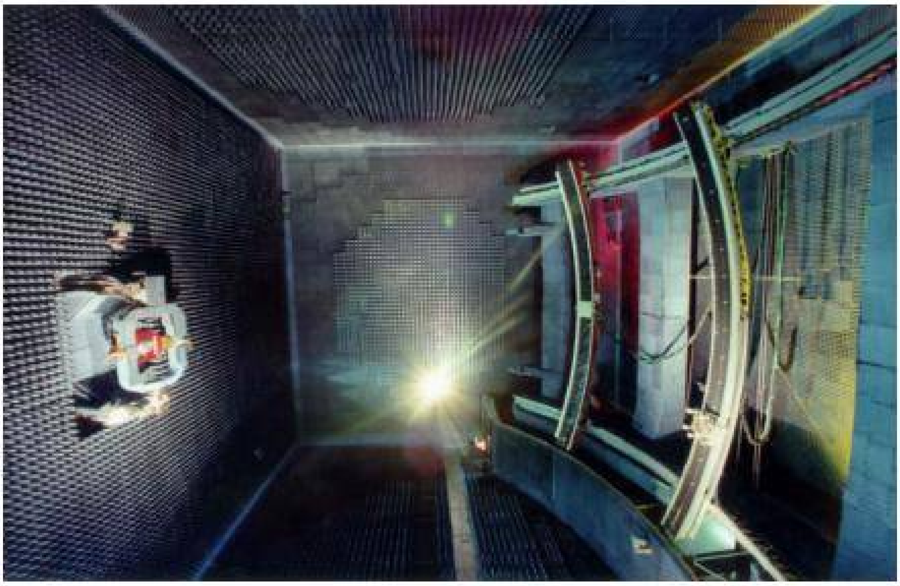

Figure 6-5: HITL Facility Example (2): UK Dstl Missile Seeker Test Facility – (Defence Science and Test Laboratory Photograph).

HITL facilities are an important test facility category because they frequently represent the first opportunity to test un-installed system components, for example breadboard, brassboard and pre-production prototypes, in a realistic RF, laser or IR environment. HITL operating environments can provide simulated terrain effects, high signal/threat density and realistic interactive scenarios. Some HITLs offer multi-spectral capability and background noise.

Modern threat representation via closed-loop hybrid threat simulators can be employed for EW effectiveness testing, man-in-the-loop interaction, and Integrated Air Defence System (IADS) networking. Secure (shielded/screened room) operations, test condition repeatability and high capacity data collection and recording are common attributes of the HITL test venue.

HITL testing should be conducted as early in the development process as possible – even if that means using a brassboard configuration. Too often pre-production hardware is developed late in a programme, making identification and correction of problems difficult. EW HITL testing provides repeatable measurements and verification of protection techniques and EW system effectiveness. Results obtained from HITL tests should be compared to predicted results from previous M&S activities. Any differences discovered in this comparison can then be analysed and the appropriate models updated and validated.

6.7 INSTALLED SYSTEM TEST FACILITIES

EW ISTFs provide a ground-based capability to evaluate EW systems that are installed on or integrated with host platforms. These test facilities consist of anechoic or shielded chambers in which free-space radiation measurements are made during the simultaneous operation of EW systems and host platform avionics and munitions. Threat signal generators, which are discussed further in Section 6.9, stimulate the EW SUT and its responses are evaluated to provide critical, integrated system performance information.

The purposes of ISTFs are:

- (Primary purpose) Evaluation of integrated avionics systems (e.g., radar, IR, communications, navigation, identification, EW systems or sub-systems, and integrated controls and displays) in installed configurations, to:
  - Test specific functions of complete, full-scale weapon systems; and to
  - Verify specific, platform-level performance against specification.
- Development and evaluation of individual uninstalled EW components, sub-systems or systems in an electromagnetically secure environment.
- Investigation and resolution of any EMI/EMC problems resulting from above.
- Determination of system reactions to EM environments of hostile and/or friendly systems whose signals cannot be radiated in free space on OARs for security reasons.
- Support of flight testing by providing pre-flight checkout and post-flight analysis capabilities (also provided by SILs and HITLs). This ground testing can aid in isolating component, sub-system or system problems not observable in other ground test facilities but crucial to system checkout prior to open-air testing.

Anechoic chamber ISTF cardinal features are indicated in Table 6-3.

Table 6-3: Cardinal Features of EW Anechoic Chamber Facilities.

FEATURE	COMMENT
Chamber size	Minimum size around 28 x 18 x 8 m. Largest known chamber is 80 x 76 x 21 m.
Shielding and quiet zones	Usually ≥100 dB over at least 0.5 – 18 GHz. TEMPEST grade. Quiet zones: one or more, dependent on chamber size.
Turntable and crane	Typically in range 30 – 114 tonnes (turntable) and 30 – 40 tonnes (crane).
Below ground room	Most have laboratory, data collection or services room below the chamber.
RF/IR threat simulators	All have RF threat simulators, usually CEESIM, AMES or by EWsT. Some have communications, navigation, IR scene simulators, radar target generator.
ECM response measurement and analysis	All have some capability, from independent equipment (spectrum, vector network, pulse modulation analysers) to comprehensive systems like the SMS.
Data acquisition and simulation	All have some capability, for RF, digital and other signal recording and to provide signals to the platform to enable 'flight' simulation.
Aircraft and other services	• Cooling, hydraulics, pressurised air, ground power for aircraft; • Fire suppression, control room, CCTV and video recording; • RAM temperature monitoring; and • Enclosed aircraft preparation area (some).
Location	Most facilities are adjacent to taxi-way, the flight line or a runway.

ISTFs fall generally into three categories, although some EW test facilities cover more than one:

- **Category I:** End-to-end systems effectiveness testing is performed on installed multi-sensor/ multi-spectral EW and other avionics systems under a wide range of realistic threat and operational conditions. These conditions require the appropriate types and numbers of players. Test events range from concept exploration and developmental tests to operational effectiveness testing. Specific tests include EW effectiveness (especially multi-sensor cued countermeasures), platform susceptibility, human factors, EP performance, weapon systems integration performance, ES systems performance, and systems integration testing.
- **Category II:** End-to-end systems integration testing is performed on installed multi-sensor/multi-spectral EW and other avionics systems under conditions necessary to prove system performance. Test events are primarily DT&E oriented with some applications to operational testing. Specific tests include: human factors, EP, avionics systems performance, and systems integration testing.
- **Category III:** Specialised testing is performed such as: RCS measurements, antenna pattern measurements, susceptibility to HPM, EM environmental effects (E3), and limited systems installation and checkout on aircraft, ground vehicles and components.

There are few aircraft-sized EW anechoic chambers in the world. Two examples are shown in Figure 6-6 and Figure 6-7, and others exist within NATO Nations, see Annex A.

Figure 6-6: ISTF Example 1: Benefield Anechoic Facility – (USAF Photograph).

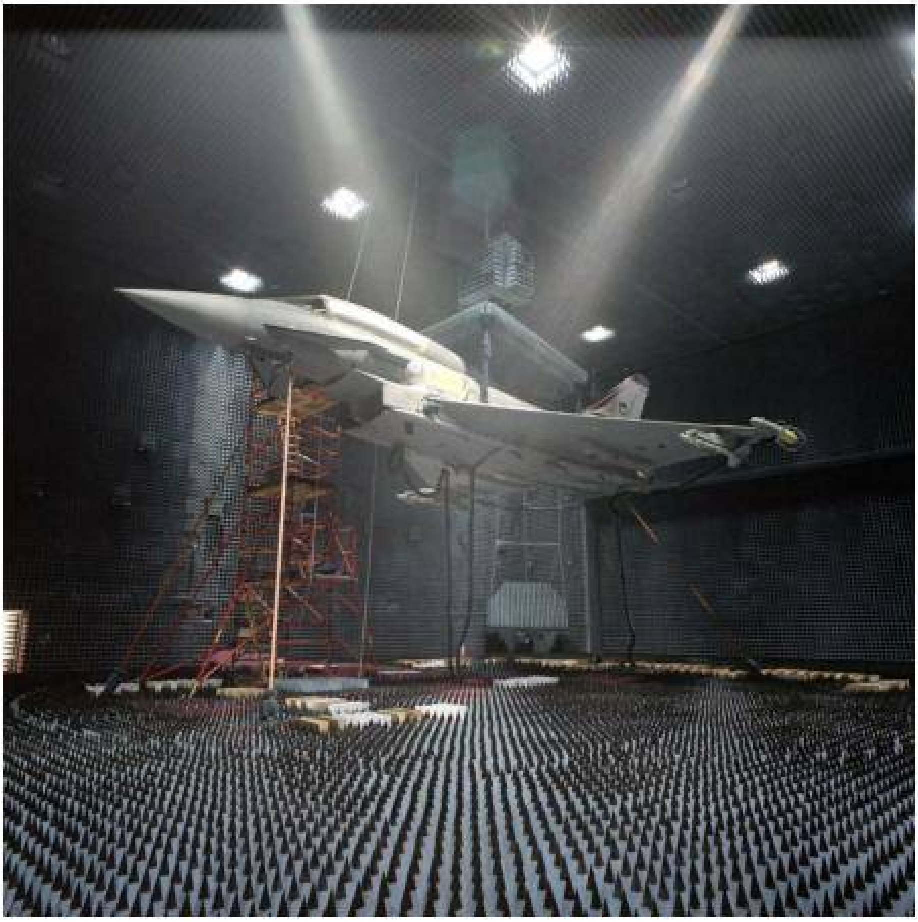

Figure 6-7: ISTF Example 2: EW Test Facility – (© BAE SYSTEMS 2010, All Rights Reserved).

These chambers can also be used:

- For IR/UV/Laser, Lightning Strike, RCS and RF Interoperability (including antenna isolation) testing of installed EW and other RF transmit/receive systems.
- To support evaluation of closed-loop performance against threats in a free-space environment.
- For platform (EW/non-EW) susceptibility testing against HPM and other DE threats.

6.8 OPEN AIR RANGES

6.8.1 Introduction to OAR Facilities

OARs used for EW and related flight testing are described in this section. Their uses are outlined, and benefits and drawbacks listed. Recognising that flight testing requires a greater level of preparation and generally costs more if a trial has to be repeated – for whatever reason – than ground-based testing, the topic of 'Flight Test Planning, Execution and Operations' is covered separately in Chapter 8.

The increasing complexity of modern avionics and EW systems, along with the growing cost of aircraft operations, has driven most test organisations to reduce the use of OAR testing wherever possible. The extensive capabilities of ground-based test facilities, increased effectiveness of M&S, and improved analytical processes discussed in this Handbook continue to enable this reduced reliance on OARs.

Nevertheless, the OAR remains an important component of the EW system testers' arsenal:

- EW T&E on these ranges is widely agreed to be the next best thing to war-fighting as this is the only 'facility' which provides a wholly realistic flight environment, including multi-spectral background, clutter, and noise.
- It is at the OAR and only the OAR where all elements of the EW system's operating environment can be accurately and simultaneously exposed to the testers' scrutiny.

Both DT&E and OT&E are conducted in the OAR environment. All known OARs used for EW T&E are owned and operated by the military, some with civilian contractor support. Most have a combination of multiple real threat systems, manned/un-manned high fidelity threat simulators ('emulators' or 'surrogates') and other (lower fidelity) simulators.

Figure 6-8 shows a typical OAR used for EW T&E, showing threat simulators.

Figure 6-8: Typical OAR Used for EW T&E – China Lake Electronic Combat Range – (NAVAIR Ranges Photograph).

6.8.2 OAR Description

OARs are used to support some or all of the following:

- EW system evaluation (DT&E/OT&E and System/Platform Acceptance), in particular of EW systems that cannot be realistically ground-tested, e.g., chaff, flares, towed/expendable/air-launch decoys.
- Initial, advanced and combat readiness training.
- Single and multi-platform force preparation and mission rehearsal. Aircrews can practice manoeuvres and tactics against a variety of threats and targets that they face in combat operations.
- Tactics and countermeasures development and optimisation.
- Development of and input to Concepts Of Operation (CONOPS), in the case of new or upgraded threats or EW systems.
- Research, Development and Engineering in support of new and upgraded EW systems.

OARs focused on EW testing are populated with high fidelity threat simulators in addition to basic range instrumentation. A typical OAR threat simulator is shown in Figure 6-9.

Figure 6-9: Typical Range Threat Simulator – Joint Threat Emitter (JTE) – (© Northrop Grumman Amherst Systems Inc.).

Some OARs also include real threat systems, both own-side/friendly and opponent. Examples are shown in Figure 6-10.

Figure 6-10: Examples of Actual Threat Systems used on OAR – (China Lake Range – Naval Air Warfare Center Weapons Division Photographs).

To be useful for most test conditions, these threat simulators are instrumented to establish a record of EW system effects on the threat. This instrumentation must be carefully planned prior to flight testing commencement to ensure that operating modes, pointing angles, receiver and/or transmitter performance, and signal processing features are accurately archived for post-test analysis of EW system performance. In some cases, additional emitter-only threat simulators (a.k.a. signal sources) are provided to create the high signal density characterising typical operational EW environments. These simulators can also be useful for some airborne integration testing where a low fidelity signal is adequate to stimulate the receiver.

OARs vary considerably in the quantity, quality, and flexibility of their threat simulation and other capabilities. The tester must establish precise test objectives and evaluation procedures prior to the selection of an OAR to ensure that these high-cost tests generate meaningful results.

OARs used for EW T&E have some or all of the features indicated in Table 6-4.

Table 6-4: General Features of OARs Used for EW T&E.

Capability	Features

Range control and instrumentation	• Time space positioning information:
	  • Air Combat Manoeuvring Instrumentation (ACMI) pods
	  • GPS with datalink
	  • Telemetry reception
	  • Range secondary, search/acquisition and tracking/TWS radars
	  • Transponders
	  • Electro-optical (Visual, IR)
	  • Laser range finders (eye-safe)
	• Airspace and exercise/test control capabilities:
	  • Interfaces to C2, air traffic control, weapon systems
	  • Audio and visual recording and display/playback
	  • Real-time 'kill' notification
	• Atmospheric measurement facilities:
	  • Land/maritime – air temperature, humidity, wind, sea state
	  • Visibility (optical, UV, IR)
	• Terrain:
	  • Realism (surface characteristics, foliage, obscuration)
	  • Ability to use chaff, flares and other expendables
	  • Ability to use active RF and EO jamming

Programmable emitter simulators and emulators • Fixed (manned/ unmanned) • Mobile • Relocatable • Open loop • Closed loop (reactive)	• Radar (search, track, surveillance) • Communications (analogue, digital, fixed frequency, spread spectrum) • Visual signature (shape, smoke trail, etc.) • Signatures: IRS, UVS, acoustic signature • IR/UV stimulators, which also help pilots become more familiar with the manoeuvres that will optimise DIRCM/flare deployment and effectiveness • Human-In-The-Loop, automatic and remotely controllable • Missile launch indication
Signature measurement	• RCS (platform, towed/expendable decoys, chaff) • Electro-optical (Visual, IR, UV) • RF emissions (radios/radars, EA, communications, navigation systems) • Acoustic
Databases	• EW Systems • Operational procedures • EW emitter parametrics • Signatures (RCS/IRS/UVS, RF emissions, acoustic) • Terrain (local and target)

6.8.3 OAR Uses

6.8.3.1 Primary Purpose

The primary purpose of OAR EW testing is to evaluate the system under real-world representative environment and operating conditions. Primary tasks are:

- DT&E flying – The final stage of acceptance testing – covers:
  - Verification that EW system performance characterised in earlier test events is representative of performance in the intended operational environment. Results of OAR tests are compared to results obtained in MFs, SILs, HITLs, and ISTFs to arrive at a complete and consistent evaluation of system performance and predicted effectiveness.
  - Final performance verification undertaken prior to customer delivery. This testing not only examines system performance when installed in the airframe, but also looks at safety in terms of, for example, safe separation of flares, chaff and towed decoys.
- OT&E flying – To validate system operational performance/effectiveness at a high level of confidence.
- Gaining an early understanding of operational features such as supportability, utility, and reliability.

In addition to the above, OARs can be used throughout the test process to establish a consistent threat baseline, act in the role of a HITL or ISTF, or provide initial 'seed' data for requirements generation. In these roles the OAR facility descriptor is sub-categorised into test ranges and airborne testbeds, which are described in the remainder of Chapter 6.

6.8.3.2 HITL Testing on the OAR

Since EW OARs typically possess a variety of threat simulation systems, they may be able to support HITL testing. While the physical configuration of a range differs considerably from the general notion of a HITL facility, see Section 6.6, the equipment available on the OAR frequently meets the tester's needs for such tests. The SUT may be located in some form of mobile laboratory (a van or trailer is common) and located near the victim hardware against which it is to be evaluated. This approach can yield advantages:

- Duplication of expensive threat simulators at multiple locations is unnecessary.
- Since the same threat hardware is employed in both the HITL and OAR test phases, an important variable is removed.
- An economy of scale is realised; overhead costs are shared between both OAR and HITL tests, and utilisation rates are improved.

6.8.3.3 Correlation of Test Resources

One of the most troublesome and difficult parts of the EW test process is the correlation of data between different test stages. For instance, if results from a HITL test disagree with results obtained during ISTF testing, the test engineers must understand the cause of the varying observations. The OAR is often viewed as the most authoritative source of test data and so correlation of all subordinate test venues to the OAR is desirable. However, such correlation is often difficult as an OAR will only have one instance of a threat that may or may not represent the combat population. As well as simulating multiple instances of emitters, SILs, HITLs and ISTFs also allow excursions in frequency, PRI, etc., not available on an OAR.

If properly structured, flight testing can be used to validate/calibrate ground test facilities and models. EW components, sub-systems, systems, and entire avionics suites can be installed in either a ground or airborne testbed or in the intended operational platform and tested on OARs.

Real-world phenomena such as terrain effects, multi-path propagation, and EMI from commercial systems (television and radio broadcasts, microwave transmissions, etc.) will be encountered during OAR testing.

The correlation process requires an understanding of each of these effects along with the behaviour of the SUT and any threat or victim systems in play. While such an analysis is technically challenging, time consuming, and costly, it usually leads to a consistent evaluation of the EW system.

6.8.3.4 Airborne Testbeds and Flying Laboratories

These flying resources are especially useful in the development of EW and sensor systems. Two sub-categories exist, those which:

- Serve as flying laboratories to carry the SUT, test support personnel, and instrumentation into the test environment.
- Include airframe or pod-mounted systems used to simulate an adversary weapon system, armament, or EW capability.

The flying laboratory has become increasingly important as EW/avionics systems have grown in cost and complexity. It offers an in-flight environment to testers and development engineers alike to make first-hand observations of system performance under realistic conditions. When assessing the flying laboratory facility for its applicability to a specific test project, one must consider the space available for installing antennas and sensor apertures, other components of the SUT, and instrumentation sufficient to accomplish the desired testing. Access to the SUT or the ability to modify software in flight may be an important consideration for some tests. In addition, the testbed platform capability to provide adequate power and cooling will always be a factor for consideration.

Airborne testbeds and laboratories range from small aircraft with pod-mounted components or systems, see Figure 6-11, to large aircraft designed for spread-bench installation and testing of EW and avionics systems. They permit flight testing of components, sub-systems, systems, or functions of EW or avionics suites in early development, often before the availability of prototype or production hardware.

Figure 6-11: Typical Airborne Testbed – (© BAE SYSTEMS 2010, All Rights Reserved).

6.8.3.5 Threat Simulation Testbeds

Threat systems and components may be hosted on range support aircraft to support flight tests and gather data to be used at other test venues. Due to the expense and operational difficulty associated with live fire tests of threat missiles against friendly platforms to evaluate end-game performance of EW techniques, "captive carry" missile seekers are often utilised. In this process a host aircraft carries aloft an actual or simulated threat missile seeker. The pilot follows, to the greatest extent possible, the flight profile commanded by the missile seeker. While very useful, this is a limitation of the capability. It doesn't follow actual missile guidance and closure rates are not realistic, so analysts need to take this into account.

The actual seeker may be mounted within the host airframe or in a pod to be carried on the wing of the host. This technique permits engineers to access the effectiveness of various EW techniques as the missile closes to close proximity of the target. In some applications multiple seekers may be carried simultaneously so that the net effects of ECM can be compared.

6.8.3.6 Tactics Development and Training

There will always be a need for some flight evaluation of EW systems, especially for development of tactics and training in support of operations and exercises. Ranges like the EW Training Facility at RAF Spadeadam (GBR), Electronic Combat Range at China Lake (USA) and Multi-national Aircrew Electronic Warfare Training Facility (MAEWTF) Polygone (USA/FRA/DEU), and the capabilities of NATO's Joint EW Core Staff, see Figure 6-12, are essential to optimising survivability and mission success probability.

Figure 6-12: NATO JEWCS Training/T&E Capabilities – (NATO JEWCS Photograph).

Some EW OARs can provide the capability for tactics development and training in operationally realistic scenarios. Aircrews can experience a dynamic and complex threat environment, including movable threats, whilst operating with other force components: Time Sensitive Targeting, Close Air Support, Forward Air Control, and Intelligence, Surveillance, Target Acquisition and Reconnaissance.

6.8.4 Benefits and Drawbacks of EW T&E on OARs

Key benefits:

- The full range of tactics and countermeasures against given threats can be explored, including dynamic closed-loop effectiveness testing against threats.
- OARs provide real-world phenomena that cannot be repeated or is difficult to repeat in the laboratory or chamber environment. These include terrain, inter-platform multi-path, chaff dispersion and realistic civilian communications and radar environments.
- OARs can be used to gather data for validating threat simulators and M&S tools and processes.

Drawbacks:

- Flight testing is expensive, especially when compared to chamber and laboratory testing.
- Range threat densities and mixes are usually very limited compared to war, due to the high through life cycle cost of real threats, emulators and simulators.
- Threat scenario flexibility is limited (governed by the range location) and results are not easily repeatable.
- Flight testing is logistically difficult, especially for NATO Nations using out-of country ranges.
- Range time slots for DT&E are usually limited due to great demand by military users for training and OT&E. This underscores the importance of gaining maximum confidence from ground testing and M&S/SE. The drawback is, in fact, usually double when a test fails: the flight has to be repeated after problem investigation and resolution and, as important, the valuable range slot has been denied to another user.

Notwithstanding aspects that can only be adequately tested in flight, chambers and laboratories are much better capabilities from an optimised T&E cost-effectiveness viewpoint than OARs for (especially RF) EW testing as follows:

- Cheaper and logistically easier than flight testing, when overall trials' costs are considered.
- Operationally representative threat densities, mixes and scenarios are achievable, albeit currently with lower simulation fidelity than real threats (noting that chambers can do some SUT tests using real threats when they are made available).
- Scientifically high test repeatability, due to tightly controlled test environment, especially in anechoic chambers.

As T&E capabilities and processes are developed, it is likely that the balance will continue to shift from EW flight testing further in favour of more ground testing and M&S. In this way residual flight testing can be more focused and have a much higher success probability, as many test points will then be confirmatory rather than experimental in nature.

6.8.5 Other EW T&E Resources for OAR Testing Support

Although not strictly flight testing or part of OARs, flight line test sets and similar EW T&E equipment are a very useful T&E resource, especially when performing installed system integration testing on an aircraft. Often, for this type of test, only a limited T&E capability is necessary – a device capable of generating a response in a SUT so that its basic integration with other systems can be evaluated. Figure 6-13 provides some examples of this type of equipment.

JSECT: AN/USM-670 Joint Service Electronic Combat Systems Tester: Platform-independent EW system and cable tester.

PLM-4: USAF flight line threat generator (a.k.a. 'Squirt box').

(USAF photograph)

Mallina: UV missile launch simulator for Missile Warners.

ACT: Aviation Crew Trainer, IR MANPADS trainer, with RF emitter optional capability.

Figure 6-13: Examples of Flight Line Testers and Other Equipment for EW T&E.

They are usually limited to confirmatory checks, rather than providing full performance verification, and are designed to increase flight test/trial success probability. A number of them are also used for training and tactics development, e.g., ground-based UV sources for Missile Warner detection and DIRCM/flare dispensing optimisation. Such test sets, dependent upon capability, can also be utilised for system testing but can be limited when compared to, for example, chamber- and laboratory-based threat simulators.

6.9 DISTINGUISHING FACTORS OF TEST FACILITIES

While the primary designation of a test facility can be used to describe it at a generic level, the test engineer must consider a number of other characteristics to determine the applicability of the facility to a particular test effort. The test plan should define the approximate characteristics that must be simulated or measured during each phase of testing. This is the starting point for selection of test resources.

As preliminary choices for test resources are made, more specific detail can be included in the test plan and then some refinement of actual tests to be accomplished at each stage or facility is possible. This iterative approach to define, refine and finally confirm test resource utilisation should be expected for most test activities. Some of the key parameters that distinguish one facility from another are discussed in the following paragraphs.

6.9.1 Number and Fidelity of Players

The total quantity of friendly and adversary players that can be synthesised during testing is important in assessing SUT performance in conditions of varying density and complexity. The ability of EW T&E facilities described in Sections 6.3 through 6.8 to provide numbers and types of platforms and emitters, especially at RF, is varied and is a key factor in determining the technically best and most cost-effective place to conduct a given test. Table 6-5 indicates player fidelity available on each facility type. Moving from 'Simulated' toward 'Real' implies increasing fidelity, complexity and cost; whilst at the same time increasing ease of test and reality of training.

Table 6-5: Player Fidelity vs. Test Facility Type.

PLAYER FIDELITY		TEST FACILITY TYPE					
		M&S	MF	HITL	SIL	ISTF	OAR
REAL: Real, fully functioning assets, e.g., aircraft, ships, land vehicles and SAMs.	SUT	No	Yes	Yes	Yes	Yes	Yes
	Platforms	No	Yes	No	No	Yes	Yes
	Threat Systems	No	No	Yes	No	Yes	Not Usually
EMULATED: Physical and/or digital models providing real stimulus at SUT. May include part-real platforms/threats.	SUT	Yes	N/A	N/A	N/A	N/A	N/A
	Platforms	Yes	N/A	Yes	Yes	No	No
	Threat Systems	Yes	N/A	Yes	Yes	Yes	Yes
SIMULATED: Digital models of players in 'virtual' scenarios. Actual sensor stimulus generated for non-M&S.	SUT	Yes	N/A	N/A	N/A	N/A	N/A
	Platforms	Yes	N/A	Yes	Yes	Yes	Yes
	Threat Systems	Yes	N/A	Yes	Yes	Yes	Yes

Traditionally, in most cases, simulated players were sub-divided into two categories; foreground and background. The foreground players can usually be precisely controlled to follow specific flight paths and have well-defined physical characteristics. Background players were generally of lower fidelity and simply added to the overall scenario density. Nowadays, many-channel RF simulators can produce up to thousands of fully complex emitters at the digital level. Inevitably, the ability to generate these emitters at RF is limited by the number of channels available, the channel pooling capability and the SUT's sensitivity to dropped pulses. This has enabled significantly better representations of operational RF emitter environments than before. Pre-defined scenarios and man-in-the-loop scenarios can be run, with pre-scripted threat engagements or ones based on weapon system engagement models within the simulator. It is now also possible to include civilian radar emitters, RF jammers and 'third party tracking', where the emitter tracks another platform in the scenario and the SUT rarely or never sees its main beam.

6.9.2 Fidelity of Digital Models

Digital models of threats, geography, meteorology, phenomenology and the players in a test scenario can differ greatly in their availability, accuracy and capability to interact with the System Under Test (SUT). Some models may permit interaction with a human operator (operator in the loop); others may be able to accurately account for the effects of ECM/EA ('EC capable').

Some models are predicated on extensive analysis and reverse engineering of the threats they represent while others are based on limited intelligence collection. The pedigree of a model is frequently defined through a rigorous process of VV&A. The tester must research the attributes of the models to be used and fully appreciate the implications of various levels of fidelity on the results, conclusions, and recommendations to be reported out of the test process.

Section 5 of [4] contains a useful discussion of this important topic under the heading 'Simulation Fidelity – the quest for affordable emulation'. A key question regarding simulation fidelity is 'How good is enough?' for a specific SUT test, since increasing fidelity generally means increasing whole life cost. This thorny question is discussed in a number of references and the nub of the question is depicted in Figure 6-14. [4],[5]

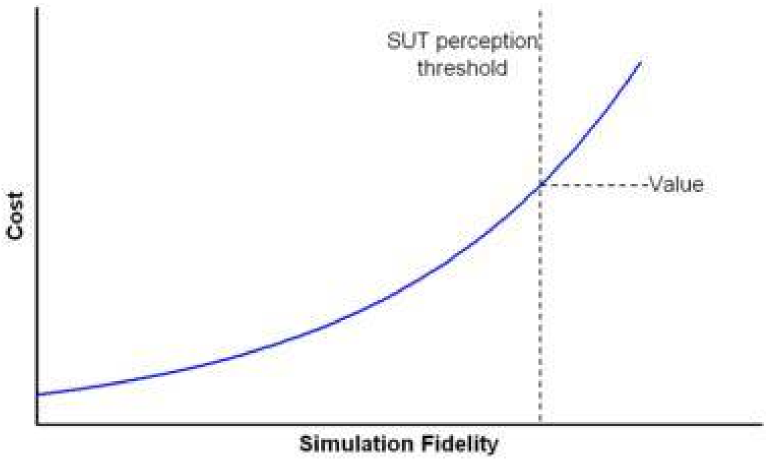

Figure 6-14: Simulation Fidelity – How Good is Enough?

6.9.3 Time, Space and Frequency Resolution and Accuracy

From the test planning process the tester should determine what analysis will eventually be accomplished. Data acquired at each stage of testing must be sufficient to support the specified analysis. Data analysis will set the baseline for both the accuracy and resolution of data to be used in evaluation of the SUT. The tester must understand the effects of data inaccuracies and errors in time, space or frequency (and combinations thereof) on the evaluation of system performance and effectiveness.

6.9.4 Signal/Scene Generation

A dominant factor in the selection of test facilities will be the capability to generate the various signals (RF) and scenes (IR/UV) to which the SUT must be exposed. This characteristic includes the frequency range, amplitude range and dynamics of the objects included in the signal/scene set. Of equal importance to the generation of signals and scenes is the manner in which these characteristics are imposed upon the SUT. In some cases they must be injected into the SUT electronics while other facilities can actually radiate the signals or scenes through free space. The tester must also consider the importance of the scenario generation process to respond to the SUT (closed loop versus open loop). The importance of these distinctions will be dependent on specific test objectives and SUT architecture.

RF threat simulators and ECM response measurement and analysis systems, see Figure 6-3, are key test facility equipment. The quantity of RF channels in threat simulators, a significant cost driver, governs their ability to generate complex threat environments. Figure 6-15 reports a survey of the quantity of RF channels per simulator. Chamber installations tend to have simulators with at least eight RF channels.

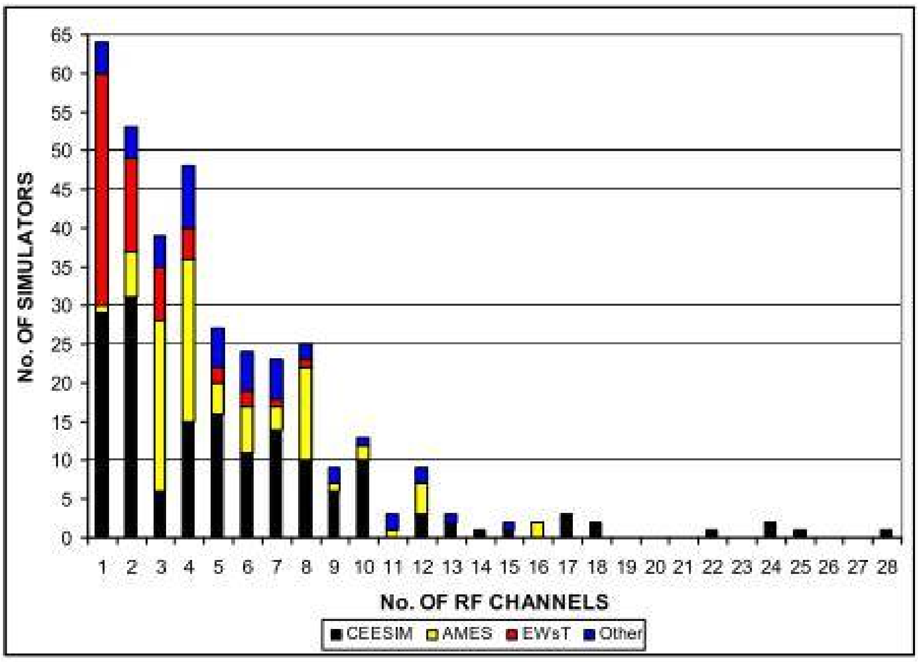

Figure 6-15: Quantity of RF Channels per Simulator – (From [6], with Permission).

Electro-optic/IR/UV scene simulation, by sensor, system or platform irradiation, or by post-sensor 'direct injection' into the SUT, is particularly challenging in the ground test environment. The advent of systems like the Real-time Infrared Scene Simulator (RISS), see Figure 6-16, has provided a step up in laboratory and chamber T&E capability – the ability to provide coordinated multi-spectral threat scenarios. [7] Such capabilities are becoming increasingly important as EW systems move toward full integration, where it may not be possible to adequately ground test the SUT in the traditional way of spectral segment by spectral segment (i.e., Radios/Radars, IR, UV, laser separately).

Figure 6-16: Example of RISS Hardware – (© Northrop Grumman Amherst Systems Inc. 2009).

6.9.5 Instrumentation

The ability to accurately capture the activities of both the test facility and the SUT during a test is primarily established by the type and amount of test instrumentation available. An important, but often overlooked concern in this area is the undesired (and sometimes unknown) effects that the facility and its instrumentation may have on the test environment. The instrumentation must accurately measure and record what the SUT was actually exposed to, not just what was intended.

6.9.6 Security

Some tests may require that all test conditions and resulting data be protected at very high security levels. This requirement may impose special constraints on how test systems are controlled and interconnected or how data acquired during a test is processed. For software intensive facilities, security must be designed into the software, not accommodated as an afterthought. The highest level of RF/EO/IR/UV security control is offered by TEMPEST-grade aircraft-sized anechoic chambers.

6.9.7 SUT Support

This characteristic defines what power, cooling, and physical positioning capabilities are offered by the test facility. It is of primary importance in ISTFs and MFs, and Table 6-3 indicates general features required. Annex A contains specific details of support capabilities offered by available test facilities.

6.10 ELECTROMAGNETIC COMPATIBILITY AND INTERFERENCE

As mentioned earlier in this section, ISTFs are often used to conduct EMC/EMI tests. While these tests are not uniquely associated with EW systems, they are crucial to overall weapons system performance.

Numerous specifications and standards dictate system design characteristics that must be met to minimise EMI and maximise EMC. To the EW engineer, EMI can result in a vulnerability that can be exploited by EA systems. On the other hand, the EW engineer must be concerned with the compatibility of the EW systems with other aircraft avionics. For instance, if the aircraft jammer produces false alarms on the pilot's RWR, it would be problematic in combat use. The following paragraphs will discuss in some detail some of the types of EMC/EMI tests EW testers should be familiar with.

6.10.1 EMC/EMI Tests

There are four types of EMC/EMI tests: Radiated Susceptibility (RS), Radiated Emissions (RE), Conducted Susceptibility (CS), and Conducted Emissions (CE). During RS testing a test antenna is used to transmit RF at the SUT to see if it is susceptible (whether it can be caused to malfunction or break), whereas in RE testing measurement antennas are used to determine whether RF emanations from the SUT exceed specified levels. RS and RE tests require a shielded room/anechoic chamber. CS and CE tests are usually performed in a shielded room but can be performed in SILs. During CS testing a current probe or similar direct coupling device is used to couple RF current down cabling into the SUT. EM energy is injected to characterise the susceptibility of the SUT to this injected RF current. Similarly, the probe or direct connection can be connected to a receiver or laboratory test equipment to measure cable-borne RF currents from the SUT. Figure 6-17 shows avionic equipment undergoing EMC qualification testing.

Figure 6-17: Typical EMC Testing of EW Equipment –
(© BAE Systems 2003, All Rights Reserved).

During emissions testing all modes of the SUT should be exercised. During susceptibility tests, an end-to-end test in addition to exercising BIT should be performed to verify proper operation. For receiver testing the input should be a mixture of various power levels within the receiver band-pass, the lowest power level being used for the highest priority signals. The goal is to determine if the receiver can process weak input RF signals while interference is being picked up by control and power lines, etc. The emission tests are non-destructive, whereas the susceptibility series of tests always run the risk of causing damage if systems are not properly designed.

During development tests, it is advisable to perform equipment and sub-system EMC/EMI testing as early in the programme as possible. Quite often EMC/EMI tests are delayed to the end because problems in other disciplines are still being resolved. The rationale is to wait and do EMC/EMI tests on the system in its final configuration. EMC/EMI tests are expensive, and there are logistic problems in moving the systems and its interfacing equipment to the EMC laboratory. But if EMC/EMI failures are detected early, they can be fixed at relatively low cost and little impact to the system schedule.

6.10.2 Platform-Level EMC Testing

EMC testing at the platform level can be further defined as Intra-system and Inter-system EMC tests. Intra-system EMC tests are used to evaluate the SUT's ability to operate in the presence of other systems installed on the platform. Inter-system tests are used to evaluate the SUT's ability to operate in the presence of external RF emitters representative of the intended operational environment.

6.10.2.1 Intra-System EMC Tests

Generally, the SUT's performance will be monitored while each other platform system is cycled through its modes, then all systems are operated together. These tests are generally conducted on an open-air test site (a type of MF), anechoic ISTF or hangar, dependent on the test in question. If the SUT exhibits adverse response to the operation of other onboard systems or vice versa, then an EMC issue has been identified. ISTFs and MFs have an important part to play in aiding testers investigate and isolate such problems, and develop and clear solutions. Whenever the systems being tested include explosive devices such as squibs for chaff and flares, adequate safety margins must be considered. Typical margins for systems containing explosives are ca. 20 dB. A 6 dB safety margin for non-explosive systems is common.

6.10.2.2 Inter-System EMC Tests

For these tests the SUT performance is monitored while the platform is radiated with RF at power levels and modulations of radar and other RF signals that may be present in the intended operational EM environment. Staircase levels of RF field strengths (power densities) and system performance are usually part of the SUT specification and test programme. Full system performance in the required operational RF environment can be arrived at by a combination of full-threat testing and extrapolation by analysis. An important inter-system EMC test for the EW T&E community concerns formation flying, where each aircraft's radar and RF jamming systems can pose a significant interference hazard to the very sensitive EW and radar receivers on the other platforms in the formation. Figure 6-18 shows a typical MF-based test used to confirm specified performance for formation flying conditions.

Figure 6-18: Typical Platform-Level Inter-System EMC Test – (© BAE SYSTEMS 2010, All Rights Reserved).

6.11 REFERENCES

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Chapter 7 – MODELLING AND SIMULATION FOR EW T&E

7.1 INTRODUCTION

This chapter provides an overview of M&S and emphasises its value to the EW T&E process. A rigorous yet pragmatic approach to its use is necessary to optimise benefits to platform projects. Reference is also made to the topic of threat simulation, a key capability that supports the EW T&E process.

M&S is the representation of 'reality' through the use of models and simulations, nowadays mostly hosted on non-specialised PCs. Testing of military systems can be considered to be a 'simulation' of their operational use, including combat. Figure 7-1 indicates this scope in the context of M&S – the electromagnetic battlespace, as can be generated by RF and EO/IR threat simulators for EW T&E.

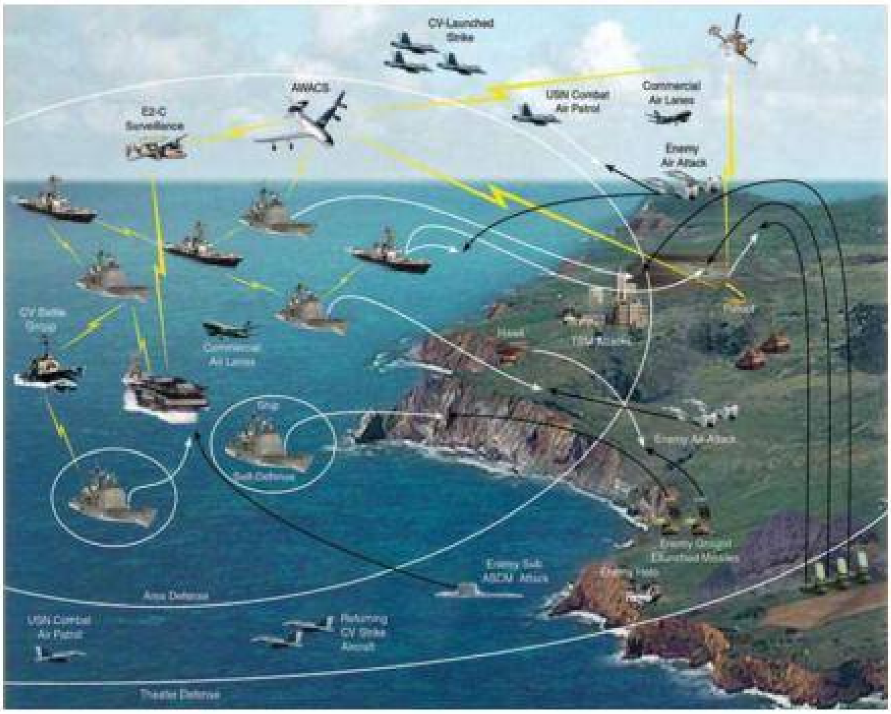

Figure 7-1: M&S Scope: The Electromagnetic Battlespace – Threat Simulation for EW T&E – (© Northrop Grumman Amherst Systems Inc. 2006).

M&S is used throughout the platform systems life cycle, from R&D to in-service support and training. Laboratory analysis, experimentation and M&S are playing an increasingly important role in T&E activities. High fidelity simulation enables mission level evaluation in a robust operational environment. Undoubtedly reducing the need to conduct physical equipment and system testing, they are not a complete solution. A shift in the balance between laboratory and physical testing is inevitable, but specialist and dedicated T&E ranges, facilities and supporting personnel will still be required. The challenge is to ensure the optimum mix is delivered and, as importantly, sustained.

The rapid rate of developments in the field of M&S and its sister domain Synthetic Environments (SE) prevents this chapter from being more than an introductory text on the topic. Whilst an overview of the through-life aspect is provided, it focuses on specific uses and benefits of M&S in the EW T&E process.

7.2 BACKGROUND, PURPOSE AND DEFINITIONS

7.2.1 Background

In the EW domain M&S was originally considered solely a tool for determining system requirements from campaign and mission requirements. Formerly also known as 'Digital M&S,' M&S now plays a crucial role in the process of acquiring and testing EW systems, and has long been recognised as a critical adjunct to ground and flight test. It is the thread that binds the various phases of the EW T&E Process together to enable a comprehensive conclusion about EW systems' fitness for purpose and effectiveness. M&S itself improves with use in the EW T&E process as test results fold back into the M&S tools to improve their fidelity and capabilities and users' confidence in them.

Historically, M&S in its wider context was problematic. The problems' primary root causes are considered to have been inadequate and/or incomplete:

- Understanding of the required fidelity of simulations/models.
- Verification of simulations/models against their designs and specifications.
- Validation and accreditation of simulations/models against the real world and relevant measured data.
- Computing power limitations (and the resultant cost required) – a significant constraint a decade ago and still a challenge.

All too often models of unverified fidelity have been used. These have led to speculation and confusion and the consequent need for further investigations – often with significant cost and time impact. Box and Draper summarised this critical fidelity factor, which remains valid today, as "*Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful*." [1]

The increasing strengths and decreasing limitations of M&S are now evident, as enabled by the last decade's meteoric rise in computing power and greatly improved understanding of the simulation fidelity; VV&A and related M&S topics.

Against a back-drop of severe affordability challenges world-wide, M&S is likely a key enabler for significant improvements in EW systems' whole life affordability. As noted in Section 6.3, US and European efforts continue apace targeting realisation of the promises that M&S offers to EW T&E.

7.2.2 Purpose

This chapter describes how M&S may provide unique and practical benefits to EW testers, project managers and programme sponsors. The EW T&E Process uses M&S and analysis prior to testing to help design tests and predict test results, and, after testing, to extrapolate test results to other conditions. At each stage of the test process, models in the simulation are replaced with hardware to achieve increasing fidelity to support evaluation. In this way M&S is part of all six resource categories described earlier in this Handbook. M&S is also used to provide frequent feedback for system development and improvement.

Models and computer simulations are used to represent systems, host platforms, other friendly players, the combat environment and threat systems. They can be used to help design and define EW systems and testing with threat simulations and missile fly-out models.

Due to the relatively low cost of exercising these models, this type of activity can be run many times to conduct sensitivity and trend analyses, to check 'what ifs' and to explore the widest possible range of system parameters without flight safety concerns. These models may run interactively in real or simulated time and space domains, alongside other combat environment factors, to support the entire T&E process.

7.2.3 Definitions

TERM	MEANING AND COMMENT
M&S and SE	It is useful to clarify subtle differences between M&S and SE, which are used extensively within [2] and [3], where both are seen to be enabling capabilities that can add significantly to effectiveness and value. For this chapter the definitions in DoD 5000.59-M, 'DoD Modeling and Simulation (M&S) Glossary' are used. [4] These definitions are: • M&S is 'The use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions. The terms "modeling" and "simulation" are often used interchangeably.' • SE is: 'Internetted simulations that represent activities at a high level of realism from simulations of theaters of war to factories and manufacturing processes. These environments may be created within a single computer or a vast distributed network connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioural models. They allow visualization of and immersion into the environment being simulated.' For the remainder of this chapter, the term 'M&S' is taken to include SE.
MS&SE	As often seen with terminology used across Nations and between agencies within those Nations, different views exist on precise meanings of M&S and SE. For example, in the UK's MoD Acquisition Framework: • 'Modelling, Simulation and Synthetic Environments (MS&SE)' is used. [5] • A model is defined as a static representation of an object and a simulation is a representation of how that varies through time. • A Synthetic Environment can comprise of those simulations, equipment and people require to represent the problem space defined to the appropriate level of fidelity.
VV&A	Here are the USAF VV&A definitions from AFI 99-103: [6] **VV&A** – Is a continuous process in the life cycle of a model or simulation as it gets upgraded or is used for different applications. **Verification** – Process of determining that M&S accurately represent the developer's conceptual description and specifications. **Validation** – Rigorous and structured process of determining the extent to which M&S accurately represents the intended "real world" phenomena from the perspective of the intended M&S use. **Accreditation** – The official determination that a model or simulation is acceptable for use for a specific purpose. There are some subtle but potentially significant differences in national terminology and application, examples of which are given in Section 7.8 and in UK DEF STAN 03-44 'A generic process for the Verification and Validation of Modelling and Simulation and Synthetic Environment Systems'. [7] Another critical point, again with national variations, is that the V&V part generally belongs to those developing the models and simulations whilst the Accreditation part is generally the responsibility of the model/simulation user.

Other common M&S terms can be found elsewhere, e.g., UK MoD's Acquisition Operating Framework. [8] Regardless of terminology and definitions, it should be stressed that whoever intends to use a model or simulation to satisfy some purpose, it is their responsibility to understand well enough how the model/ simulation works to be able to determine if it will adequately satisfy their requirements.

7.3 OBJECTIVES

The objectives of M&S in the EW T&E process are to:

- Prove design concepts prior to final testing.
- Demonstrate system performance:
  - For elements that are either too complex or too expensive to verify by testing.
  - To supplement testing by interpolation between sparse data points.
  - To extrapolate measured test data into un-testable or unavailable regimes.
  - Where test repeatability is difficult or where tests would yield unacceptable error bounds.
- Define safety footprints or limits.
- Increase sample size once confidence in the model is established.
- Define test facility requirements, e.g., number and types of threats, airspace required, control of background noise and emitters, and instrumentation.
- Define and optimise test scenarios.
- Select test points, i.e., successful results would not indicate the need for additional heart-of-the-envelope testing.
- Predict test results for each test objective.

Provide a complex, operationally realistic environment.

7.4 M&S CATEGORISATION AND LEVELS OF COMPLEXITY

EW models and simulations are generally categorised and constructed to the levels of technical complexity commensurate with their intended use, as shown in Table 7-1. This Table expands upon Table 6-2 in the introduction to M&S within Chapter 6.

Table 7-1: M&S Categorisation and Levels of Complexity.

LEVEL	TYPICAL APPLICATION	COMMENT	TYPICAL OUTPUTS
Campaign (Operations, Theatre)	• Optimum force allocation, force mix studies. • Balance of Investment trades, e.g., Strike vs. ISTAR assets. • Availability analysis, i.e., sortie generation rates, concept reliability and maintainability. • Logistics and spares support and footprint analysis. • Force-on-Force interactions occurring **over several days**.	This level incorporates the Command, Control, Communications, Computers and Intelligence (C4I) contributions of joint-Service (i.e., Army-Air Force-Navy) and Allied Forces operations against a combined threat force (force-on-force). It integrates the various missions into regional, day and night, and joint operations, and assesses the input of EW on force effectiveness. Campaign level is similar to mission level except that a campaign is a many-on-many simulation including the impacts of having to sustain the mission for an extended period of time. It evaluates effectiveness and force survivability of friendly, multi-platform composite forces opposing numerous threats, but also includes the issues associated with human factors, logistics (including battle damage repair), and attrition.	Answers to the questions: • Did we win the campaign/war? • How long did it take? • At what overall cost?
Mission and Multi-Mission	• Weapon system concepts and CONOPS trade-offs (e.g., survivability). • Force mix / group operations analysis (e.g., value of support jamming). • "Many on Many" interactions **over several hours**.	Multiple weapon systems level models (with varying degrees of detail) combined into a simulated mission to analyse mission effectiveness and force survivability of friendly, multi-platform composite forces opposing numerous threats (many on many). Mission level models frequently include the impact of the enemy's command and control capability on the outcome. Sometimes contractors are tasked by defence ministries to use this level of modelling to evaluate contributions and cost of various configurations. Thus in some cases, the contractor thus defines (for example) required levels of signatures and DAS.	Answers to the questions: • How many sorties were required to achieve the given mission objective? • How many engagements did we face? • Probability of successfully completing the mission.

LEVEL	TYPICAL APPLICATION	COMMENT	TYPICAL OUTPUTS
Engagement	• Platform level, e.g., weapon system, sensor suite and DAS trades. • Tactics exploration and optimisation. • Few on Few engagements, **over many minutes**.	Weapon system level models are used to evaluate effectiveness, including associated tactics and doctrine, in the context of an integrated weapon system engaged with a single (one-on-one) or a few (one-on-few) enemy threats (e.g., SAM systems) in a simulated scenario.	• Aircraft 'state vector' at end of engagement, i.e., position, speed, fuel, weapons, expendables, etc. • Engagement outcome, e.g., in an 'm vs. n' air-to-air combat, how many emerge on each side unscathed / needing to return to base. • Length of engagement and significant events, e.g., point of detection, recognition, weapon release, threat emitter activity.
Engineering (System)	• EW sensor and ECM performance analysis. • Alleviating RF interoperability issues. • Analysis of system interaction with RF and electro-optical/IR/UV environment, e.g. natural and man-made clutter. • One vs. One system interaction **over many seconds**.	The main difference between engagement level models and system level models: the former tends to emulate the effect of EW often assuming a lot, whereas the latter simulates 'the physics' of the EW interaction and assumes very little. A key element of this level for EW, radar and radio systems is establishing ***optimal installed performance***, as platforms – especially aircraft – invariably preclude achieving theoretical maximum performance.	• Antenna gain vs. angle tables (for on board ECM, towed decoy, threat radar). • Optimal RF/EO/IR/UV sensor and effector (ECM) positions on platforms, to maximise survivability and mission success probability. • ECM technique effectiveness vs. given threats. • Jammer power, bandwidth and other requirements. • Chaff dispersion rated and characteristics. • DIRCM cueing accuracy from MW models. • RF/IR/UV threat emitter scenarios.
Engineering (Sub-System)	• Component R&D. • Circuit analysis. • Interactions typically occurring in **fractions of a second**.	Modelling used to examine technical performance of an individual component or LRI/LRU or sub-system in accordance with their intended designs.	• Impedance requirements. • Power and cooling requirements. • Switching speeds. • Memory requirements.

Categorisation schemes vary, although there is significant commonality – the differences largely concern the resolution required of the models and simulations, i.e., how much detail is appropriate for the questions being asked? For example:

- In some schemes the 'Campaign' level is called 'Operations' and in others 'Theatre,' whilst others have Campaign and Theatre as separate levels. In this Table all three are considered to be under the 'Campaign' header.
- Likewise some schemes only have an 'Engineering' level, whereas others decompose this into 'System' and further into 'Sub-System,' 'Equipment' and 'Component (or 'Circuit'). In this Table only two levels are used: 'Engineering (System)' and Engineering (Sub-System).

7.5 APPLYING M&S IN THE EW TEST PROCESS

M&S supports EW testing throughout the EW Test Process as shown in Figure 1-6 to plan (predict), conduct (test), and analyse (compare) the test programme and evaluate SUT performance. M&S tools consist of two parts: the battle environment and the SUT. The battle environment includes software representations (models) such as the enemy's weapon system (threat) and the propagation environment. The SUT (often referred to as the Digital System Model, DSM) includes software representation of the friendly weapon system, such as the aircraft, including any electronics critical to the evaluation.

7.5.1 Defining System Requirements

M&S tools are used to examine theatre, campaign, and mission needs to determine the requirements for new or upgraded EW capabilities. Once a requirement is established, M&S tools are used to determine performance characteristics required in the EW system.

EW system performance requirements are stated as MOEs that are decomposed into MOPs from which test objectives can be derived. M&S plays a key role in the process of defining test requirements based on what information is needed about the EW system. MOEs and MOPs become the basis for planning an EW test programme, and M&S provides the tools to feed back the EW performance observed during testing into the original simulations used for determining EW performance requirements.

7.5.2 M&S in the EW Test Process

With MOEs in hand, the test team begins the test process designed to gain incremental information on the EW system's performance, increasing confidence the system will perform effectively in combat. Figure 7-2, which is similar to Figure 1-11, shows a logical flow of test activity from left to right.

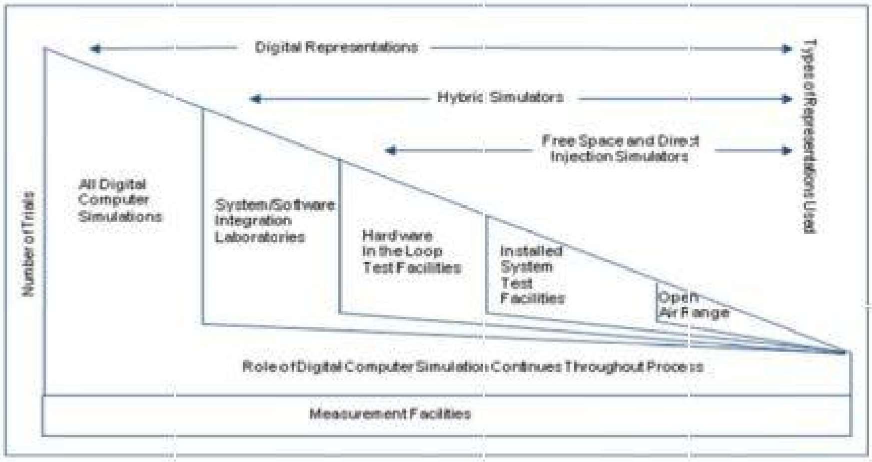

Figure 7-2: Activities Within the M&S Interface.

MFs (such as radar cross-section and antenna pattern measurement ranges) support the process continuously as needed. The majority of activity at these facilities occurs early in the process. All computer simulation also begins early in the process. It is used to assist in design, trade-off studies, system integration decisions, and test planning. As this chapter shows, M&S provides support throughout the EW test process. SILs provide the capability of testing individual EW system components (for instance, in 'brassboard' configurations) and sub-assemblies in a laboratory environment. HITL facilities allow testing the interactions of assembled EW systems with a simulated environment representing the threat situation. Frequently, the simulated environment at the HITL will include threat hardware integrated with simulation to create the battle environment. Once the EW system is integrated with other avionics on the aircraft, the integrated systems are tested in the ISTF to ensure compatibility of the various systems involved and that the EW system performs as expected when connected with other aircraft systems. The final test phase is flight testing at an OAR.

Figures 1-6 and 1-11 emphasise the continuing role of M&S throughout the EW Test Process. At each test facility, software tools play important roles in supporting test conduct and interpreting results. The roles of M&S at each test phase are very similar. Figure 7-2 graphically depicts how M&S fits in to these test phases. It is not appropriate for all M&S activities to be employed at all test phases, so the functions shown are turned on and off depending on the specific needs of the test.

A 'seamless' test process greatly benefits from continuity in the M&S functions shown in Figure 7-2. The M&S tools used for test support should be used to support simulations used at each facility. For instance, the target representation used at the HITL should be traceable to the target representation in the M&S. Models must have the appropriate fidelity to achieve the test objectives for a given phase of testing. The functions shown in Figure 7-2 apply generically to any EW test facility, but the model fidelity required can vary from facility to facility. For instance, in early phases – such as the SIL, a basic model of the SUT may be sufficient for some T&E activities. In subsequent phases, a more detailed and higher-fidelity system model is generally required, depending on the evaluation objectives.

An overview of how M&S facilitates and shapes EW testing is shown in Figure 7-3. The M&S function in each block is briefly explained later in this chapter along with a short example of each. M&S plays key roles before, during, and following each phase of testing. M&S allows system characteristics measured and reported in engineering units to be translated into terms reflecting overall system effectiveness. Through analysis using M&S, results from one phase of testing can be used to define and optimise testing at subsequent facilities. This makes M&S an excellent risk reduction tool in the development of a friendly weapon system. This is a valuable capability since, in general, the expense of test hours increases as testing progresses from SILs, through HITL facilities and ISTFs to OARs.

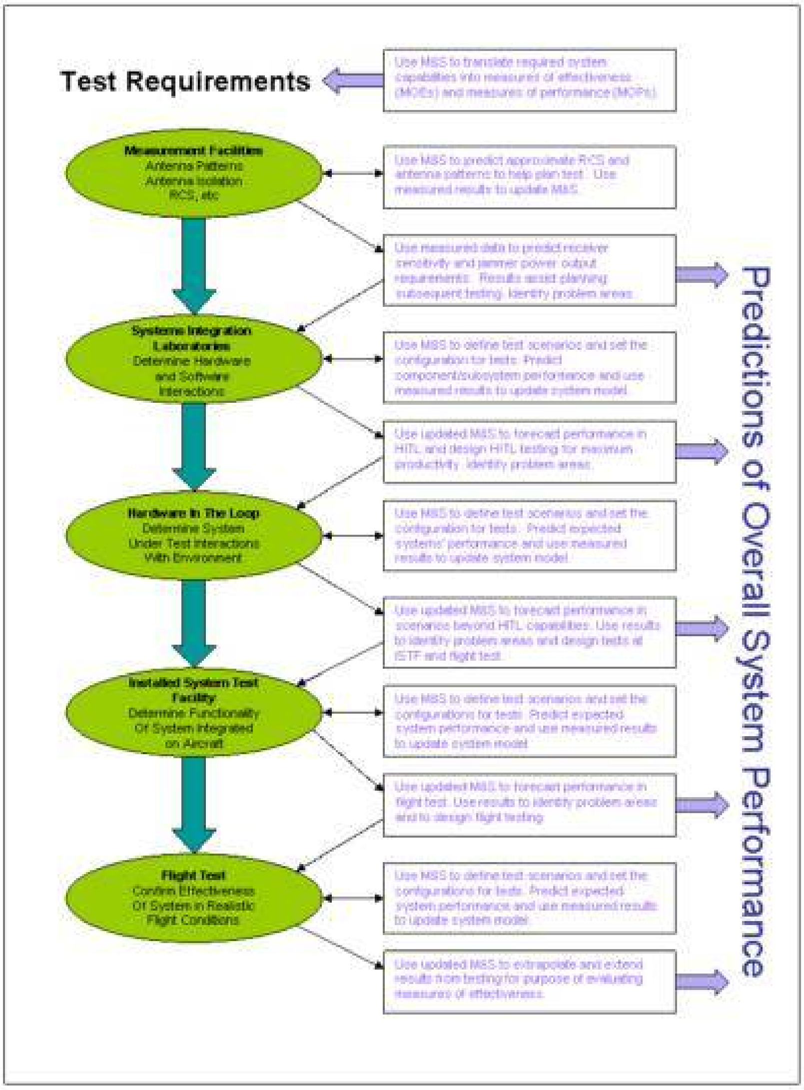

Figure 7-3: M&S Activities at Test Phases.

Figure 7-4 shows the DoD Live Virtual Constructive (LVC) continuum. Within the EW T&E activities there is likely to be mix of simulations and real equipment. The mix of this will differ through the life cycle depending on the maturity of the solution. Within this construct T&E could be performed earlier in the life cycle than it has been done traditionally, but with more simulation-based solutions. As the solution matures, real equipment will gradually replace the simulations providing a gradual de-risking process.

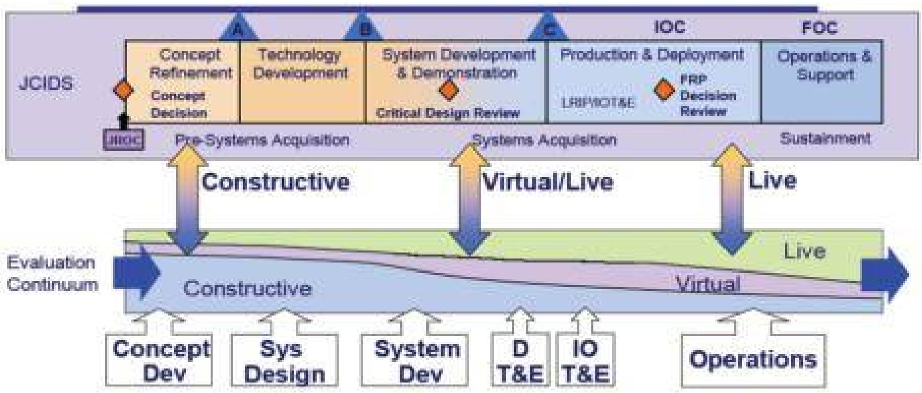

Figure 7-4: M&S Activities Supporting EW T&E: The DoD LVC Continuum.

At the conclusion of the 'test' phases, M&S plays a major role in extrapolating performance observed in test to operationally realistic scenarios as defined in the requirements document for the system. During the test process, confidence grows in the conclusions concerning the weapon system's performance. Confidence is also increased in the M&S tools since measured results provide feedback for model refinement and validation. The completed set of M&S tools can then be used to explore the EW system's performance in conditions that cannot be tested at the various facilities. At completion of testing, the validated M&S tools are available for a wide variety of analysis applications.

7.6 M&S ACTIVITIES SUPPORTING EW T&E

The following paragraphs provide generic descriptions of each of the key M&S applications.

7.6.1 Quantify Test Conditions

The use of M&S to quantify test conditions provides a firm foundation for subsequent testing using the EW T&E Process. An Analysis of Alternatives (AOA) is conducted to develop mission scenarios and evaluate effectiveness and cost trade-offs. At this stage, there are no detailed system parameters available (for example, known performance in terms of response times, jamming waveforms and the like) nor specific system performance requirements. The AOA first determines if future defence strategies require the development of a new weapon system or sub-system.

The AOA process develops operational mission scenarios including target analysis, threat system deployment, and development of realistic mission profiles. The missions are simulated and analysis of the resulting interactions between the weapon system and the threat quantifies the frequency of occurrence that specific threats engage the aircraft. The parameters of the engagement conditions such as range, offset, and the presence of other threat systems and their emissions are also predicted. The predominant and most stressing conditions challenging system performance are identified by the M&S analysis. These provide quantified descriptions of candidate test conditions that are used to design test configurations for each of the test facility categories and specific test runs.

7.6.2 Design Tests

Based on the candidate test conditions, M&S is used to design and plan tests which obtain the most usable test points per test hour. The candidate test conditions are refined to account for limitations of the test facilities to define Reference Test Conditions (RTCs). M&S tools are then configured to simulate the RTCs for designing a set of test runs that vary key aspects of the test conditions. These are the Planned Test Conditions (PTCs) which result in the most test points for the test run matrix.

This use of M&S helps the test team to define an efficient test matrix by identifying conditions where MOP values change so no more sample test points than are needed will be planned. This improves overall test efficiency by concentrating test resources productively. Because flight test hours are usually limited based on funding constraints, using M&S for test design will not always reduce flight test hours, but it does help focus the flight test on critical data requirements.

7.6.3 Predict Test Results

The test team can use M&S to predict the expected values for each MOP in the test matrix. The predicted values support 'Quick Look' analysis to detect problems with the test execution if the test results differ significantly from the predictions. Test prediction is not a new concept nor is the use of M&S to help design and predict results. For years, M&S has been used in this fashion for flight performance testing and for space programmes. In their application to the EW Test Process, M&S tools become more detailed and accurate as they are validated with test data. The test team can also use the M&S tools to control the instrumentation and data reduction process by identifying essential data acquisition points. In many cases, data obtained from M&S can be used to test the analysis process to be used for actual test results. This can uncover problems in the analysis processes before actual testing begins.

7.6.4 Simulate Elements

Simulation plays a key role in many phases of testing. For instance, accurate simulations of threat radars and other emitters in the scenario are necessary to provide sources of realistic signals used to test the SUT capabilities in a dense signal environment in the SIL. This topic is discussed later in this chapter.

Another important element often available only in a simulation is the threat missile seeker hardware. For HITL testing of the SUT interaction with seeker-dependent missiles, accurate models of the missile fly-out are necessary to obtain proper seeker geometry and RF/IR/UV conditions for the test. M&S supports these and other requirements to construct meaningful test conditions by providing suitable output representations of threat activity from validated modules representing their hardware counterparts.

7.6.5 Quantify Test Results

M&S provides the link between what can be measured from testing and what must be known about the associated impact on aircraft survivability at all phases of testing. M&S can aggregate measured data from testing and project it into predicted system effectiveness terms that allow more direct evaluation of system capabilities.

7.6.6 Compare Predicted and Test Results

It is important to compare results predicted for the test using M&S with actual results. One reason for doing this is to gain confidence in or refine the M&S. Arguably, a more important reason is to 'sanity check' test results. In cases where measured results disagree with predictions, there is always a chance that problems with the test setup, execution, or data collection are the cause. Having confidence in the predicted results allows problems with the test to be quickly identified and corrected.

7.6.7 Extrapolate Test Results

For various reasons (cost, time, resource limitations, or safety), testing cannot collect measured data at every possible point in the region of interest. M&S can be used to increase the sample size by simulating those events that could be encountered operationally but could not be included in the test design.

M&S is also used to extrapolate results to higher level MOEs than can be directly tested. For example, tracking error, which is a MOP, is extrapolated to miss distance by simulating the missile fly-out. The miss distance for numerous test runs is then analysed to obtain the Reduction in Lethality MOE (see Annex B).

Validation of the M&S models and extrapolation of results provide the test team with tools to connect the MOPs to system effectiveness, which make test results meaningful to programme management in reaching decisions concerning the programme.

7.7 EXAMPLES OF APPLYING M&S DURING TEST PHASES

This section describes how a test team can use M&S at each test phase. It is not a comprehensive description of M&S throughout the EW T&E Process, just a sampling of how M&S can be used. One example MOP is selected for each process phase to illustrate contributions of M&S at each test phase.

As testing progresses through the process, the test team collects more measured data. As a result, there will be a reduction in remaining MOEs/MOPs to be predicted through simulation. As a specific example of this process, measured installed antenna patterns obtained at the measurement facility will replace the engineering estimated antenna patterns in the DSM. The MOEs/MOPs will be computed or re-computed using the updated model(s).

7.7.1 MF Example: Antenna Pattern Measurement for Field-of-View MOP Assessment

A platform's RWR antennas must provide visibility throughout the required range of azimuth and elevation. If the achieved field-of-view coverage is inadequate, the RWR will not provide warning for threats located outside the achieved field of view.

Design Test: The DSM will be used to specify sampling intervals and resolution required in measurements to ensure the resulting collected data are sufficient (but not wasteful 'overkill') for supporting subsequent modelling which uses the measurements as input data.

Extrapolate Test Results: The DSM will be stimulated with analytically combined measured antenna pattern data to observe predicted SUT performance in response to frequency and polarisation combinations not actually part of the measurement plan.

7.7.2 SIL Example: Detection Range MOP

The platform's RWR must warn the aircrew at a range from the threat that allows employment of suitable countermeasures. If the achieved detection range is inadequate, warning time will not be adequate to allow effective countermeasures.

Design Tests: SAMs and Airborne Interceptor systems, emitters and environment models can be used to generate expected power levels for testing jammer and RWR threat detection capabilities. The corresponding values of power will be used to design the test setup and data collection efforts. In other words, the test team will use this power as the starting point and proceed up or down in the scale as necessary to characterise detection capability.

Predict Test Results: The DSM, threat, environment, and aircraft models will be used to predict the range between the aircraft and threat at which the SUT initially detects each threat along the test scenario.

Extrapolate Test Results: Validated DSM models will be used to extend the measured results to include assessment of detection range performance against emitters not available in the SIL. This allows follow-on analysis to incorporate newly assessed threat capabilities and opens up the possibility of deployments without re-visiting the SIL facility.

7.7.3 HITL Example: Track Error MOP

Output jamming waveforms must cause sufficient degradation in threat tracking of the aircraft to prevent damage or destruction by a missile or AAA.

Design Tests: Threat models capable of predicting threat radar responses to ECM (called 'EC-capable' models) are used to evaluate the capability of the self-protection system to achieve a given degradation in threat tracking performance at various target offsets and altitudes. Resultant effectiveness estimates are used to design the HITL test setup and to specify offsets and altitudes.

Predict Test Results: DSM, threat, and environmental models are used to establish expected values of the resultant track error. Threat models used for this must be EC-capable.

Extrapolate Test Results: DSM and EC-capable threat models are used to extend results measured in the HITL to include assessment of SUT-threat interactions in conditions not actually measured at the HITL, to show SUT sensitivity to changes in environmental and/or threat factors that influence tracking error.

7.7.4 ISTF Example: Pulse Density MOP

Systems must be capable of collecting and processing all incident pulses expected in the aircraft scenario, subject to the specified tolerable pulse drop-out. If achieved pulse processing capability is inadequate, the system cannot effectively perform when conditions of pulse density are above the achieved capability.

Design Tests: Emitter, threat, and environmental models will be used to establish incident signal conditions at representative pulse densities for an operational scenario. These signal conditions will be used to design the test set-up and data collection effort at the ISTF.

Predict Test Results: The aircraft, DSM, emitter, threat, and environmental models will be used to predict SUT performance in the presence of the signal conditions derived above.

Simulate Elements: Motion of aircraft and other moving platforms of interest is simulated using M&S.

Extrapolate Test Results: Full simulation including the aircraft, DSM, emitter, threat, and environmental models can expand the scope of SUT evaluation by extending it to combinations of laydown, scan schedules, mission profiles, and other conditions not actually measured at the ISTF.

7.7.5 OAR Example: Reduction in Shots MOP

Jammers must sufficiently decrease the opportunity for missile launches with ECM versus without it. If sufficient shot opportunities cannot be denied, overall jamming effectiveness will be inadequate.

Design Tests: Aircraft, DSM, and threat models will be used to design flight tests that provide shot opportunities covering each tested threat system's engagement envelope and the mission envelope of the aircraft. Results of simulation will be used to design data collection, select threat rules of engagement (such as cueing and firing interval), and reference time TSPI coverage requirements.

Predict Test Results: Simulations used to design the flight tests will be run using derived test conditions to produce expected shot rates achievable by the threats under ECM and non-ECM conditions.

Extrapolate Test Results: M&S is used to extend results achieved at the OAR to include relevant threat density and combinations that are not available at the OAR, and, where necessary and possible, to include effects of tactics that were not employed during flight testing due to test restrictions.

7.8 SIMULATION FIDELITY, CREDIBILITY AND FITNESS FOR PURPOSE

7.8.1 M&S Fidelity and VV&A – RF Threat Simulation as an Example

This section discusses fidelity and VV&A as applicable to M&S as used in EW T&E. Sections 6.9.1 and 6.9.2 have already touched on fidelity under the topic of distinguishing factors of test facilities. This section expands on the topic with specific reference to RF threat simulators, a mainstay of many EW T&E facility categories. [9] As will be seen in this section, this can be seen as a general case for the consideration of any model or simulation to be used in the EW T&E process.

7.8.2 Definitions

There are many views of the meanings of the terms used to describe how faithful a representation of something is provided by a 'model' or a 'simulation'. Many years ago definitions were relatively straightforward: a simulation could have high or low fidelity. At its highest level of fidelity, the simulation became an emulation of the item concerned. As such it was identical to the item in all respects relevant to the emulation's use.

Nowadays terms such as 'model,' 'simulation/simulator,' 'emulation/emulator,' 'replication/replicate,' 'surrogate' and 'hybrid representation' often have multiple meanings, dependent upon Nation, agency, technical sector/domain, topic/aspect/item of concern and stage in the platform/equipment life cycle. In some countries references exist to aid clarity of this multiple usage but these are not international standards per se.

It is thus necessary to define the meaning of specific terms in the context of this section:

- **RF Emitter Simulation**: Imitation, at RF, of the real-world characteristics and behaviour of one or more RF emitters, to a given level of fidelity. Note: Simulations/simulators are usually more cost-effective than using real threat weapon system radars for most test missions.
- **Simulator Fidelity**: The measure of the quality of RF emitter simulation when compared to the real emitter, for all those spectral, spatial and temporal aspects relevant to the simulator's use in EW T&E.
- **Emulation**: Highest fidelity simulation, where a perfect EW receiver could not discriminate between the emulation and the real emitter. Note: Emulations/emulators are useful where the use of the real item is either not necessary or is undesirable.

- **Verification**: The process of determining that an EW receiver system, when tested using a threat simulator incorporating threat emitter models, meets its contractual specification.
- **Validation**: The process of determining whether the:
  - Simulator's output, when programmed with threat emitter models, is adequate for its intended use in the T&E process.
  - SUT, when programmed with theatre-specific Mission Data, correctly identifies and reacts to real/simulated threat emitters.
- **Accreditation**: The process of determining whether a simulator's rendition of threat emitters is suitably realistic, robust and credible.

7.8.3 Threat Simulation Fidelity

Threat simulation fidelity is dominated by two factors – threat emitter characteristics programmed into a simulator and the simulator's capability to translate those characteristics into a faithful representation of the RF signals that would be received by the SUT's antennas when radiated by the real threat under combat conditions. As with any simulation, a threat simulator's capabilities need to be fully understood in terms of the VV&A processes for M&S, and for SUT performance V&V. [10]

Table 7-2 depicts VV&A from a threat simulator standpoint.

Table 7-2: Threat Simulators and VV&A.

PROCESS NAME	OBJECTIVES	KEY QUESTION	PROCESS ACHIEVES	DONE BY
VERIFICATION	Uses simulator to confirm that SUT meets its specification	Was SUT built correctly?	Tests FUNCTION and PERFORMANCE	SUT suppliers and platform/ systems integrator
VALIDATION	Confirmation that: • Simulator produces adequate representation of emitters • SUT, when programmed with theatre-specific mission data, correctly identifies simulator-generated emitters	Do simulator-generated emitters look and behave sufficiently like the real thing?	Evaluates FIDELITY	Military, often with Industry support
ACCREDITATION	Certification that [simulator + threat emitter data] is adequate for proving [SUT + mission date] is fit for intended military purpose	Can simulator be used to optimise and validate mission data for EW receiver systems?	Determines CREDIBILITY	Military, often with Industry support

Various methods are used to confirm (or 'validate') the fidelity of a simulator's rendition of threats. National methods vary and a good example is the US CROSSBOW (Construction of a Radar to Operationally Simulate Signals Believed to Originate Worldwide) process, run by a tri-service technical agency established for the common development of EW RF simulators. It assures that simulators and models are consistent with intelligence agency threat estimates and that validation procedures are being followed. It then certifies simulator-model combinations for use for specific EW T&E cases via accreditation tests.

7.8.4 Fidelity, Affordability and the Limits of M&S Utility

Whilst it is philosophically possible to satisfy all VV&A requirements for any given system by M&S alone, there are significant obstacles that preclude its achievement. The primary reasons are affordability and computing power. Generally a better simulation needs improved fidelity and, generally, increased fidelity equals increased cost of implementation and model/simulation maintenance. It is thus considered unlikely that systems will ever be fully cleared by M&S also, i.e., without some residual element of SUT ground test and flight trials.

Again using the example of RF threat simulators, it has been long recognised that achieving emulation of combat air RF environments using simulators is utopian. The combination of affordability, highly complex electromagnetic interactions experienced in the real world and simulator technology limitations is likely to constrain simulations to limited resemblance to the high-pulse density, confusing electromagnetic 'mush' that is often the electronic battlespace in modern conflicts.

However, with reference to the definitions in Section 7.8.2, a perfect EW receiver is unlikely to ever exist. Thus the question is really whether a simulator provides sufficient fidelity for the SUT to be unable to discriminate between its outputs and emitters in the real-world RF environment. This, as for other areas of avionics T&E, is a question of adequacy – there is no need to generate significantly better fidelity than the SUT can measure.

In terms of adequacy, there are a number of rules of thumb that suggest T&E equipment should be able to simulate/generate/measure to an order better than the SUT can measure. Whilst often possible in the digital context, this is less easy in the RF world but modern simulators can, for most parameters, easily exceed the parameter range of the SUT. It is less easy, even given today's technology, to significantly improve on parameter accuracies and resolutions, though few problems have been reported in this area.

It is clear that much more can be achieved by M&S, but that the affordability boundary between M&S and testing needs to be determined carefully for each function and performance element requiring verification.

This situation has been examined for RF threat simulators, see [9], where a number of enhancements to the then existing state-of-the-art simulator were identified that appeared to promise the fidelity level where more of the T&E currently done by flight testing against real threat emitters could to be executed within the anechoic chamber and laboratory environment – offering cost saving, repeatability and investigation benefits. Once the above simulation fidelity level has been realised, the need for any further fidelity increase will need to be cost-benefit traded to determine whether the required tests might be better conducted via OAR flight trials. This situation is also in line with the US Defense Modeling and Simulation Office's view on 'State of the Art in Fidelity'. [11]

7.8.5 Fidelity Description

When determining fidelity requirements for a model or simulation it is important to provide quantitative fidelity descriptions if the model/simulation must produce critical parameters to specified levels of accuracy. [12] Qualitative (High/Medium/Low) descriptions lack the information content necessary to support technical decisions about simulation fitness for a particular purpose. Fidelity needs to be characterised in terms of resolution, error/accuracy, sensitivity, precision and capacity.

7.8.6 M&S Credibility and Fitness for Purpose

Maximum benefit is reaped from models and simulations when their function and outputs are credible and their fidelity is sufficiently high to be affordably fit for purpose for the task at hand. Much has been written on these topics, too much to individually reference in this Handbook. The interested reader is referred the NATO Modelling and Simulation Working Group, see Section 7.9, and their National M&S agency, for guidance and other sources of information.

M&S credibility is hugely influenced by the overall experiment design process (use the right models together with the right data) and the overarching V&V process applied to that.

There are simulation processes that exist that are aimed at providing transparency and fitness for purpose. These are primarily the Federation Development and Execution Process (FEDEP) and Distributed Simulation Engineering Experimentation Process (DSEEP). [13],[14] Note that FEDEP, although known to still be in use at the time of this Handbook's issue, has been superseded by DSEEP, which was approved as a recommended IEEE standard in January 2011.

The DSEEP process builds on the FEDEP process and is a generic process which is clarified by the following steps, whose content is also outlined below:

- **Define Simulation Environment Objectives (Step 1)**
  - **Identify User and Sponsor Needs**: The requirement to produce an M&S application is started by a specific need. It is important to establish a clear understanding of the User's and Sponsor's goals.
  - **Develop Objectives**: A detailed set of specific objectives are developed and documented. The capability of M&S to be able to address these objectives is assessed in terms of cost, required timescales, risks, availability of personnel, supporting tools, security issues, network constraints, potential solution approaches, and facilities.
  - **Conduct Initial Planning**: Initial planning documentation is produced in terms of the Simulation Environment Development and Execution Plan (SEDEP), incorporating an approximate schedule with identification of major milestones, and addressing such issues as configuration management, test, security and V&V.
- **Perform Conceptual Analysis (Step 2)**
  - **Develop Scenario**: The objectives identified in Step 1 are assessed in terms of how they might be represented in the real-world domain, and from this a prototype scenario is developed. Several vignettes may be produced in order to fully satisfy the objectives. Scenario information should include the number and types of all the main entities, their positions, capabilities and behaviour, and scenario exit criteria. Geographical location and environmental conditions should also be specified. Potential reuse of previously established scenarios should be considered.
  - **Develop Conceptual Model**: From this information, the conceptual model can be established and documented. This is a real-world, implementation-independent representation which transforms the original objectives into a set of functional and behavioural descriptions designed to meet them.
  - **Develop Simulation Environment Requirements**: Detailed requirements for the simulation are established from the conceptual model and extend to consider the simulation environment

specific issues such as exercise control, monitoring, data logging and analysis, networks, test criteria, etc. Documented requirements should be traceable from the conceptual model to the original objectives.

- **Design Simulation Environment (Step 3)**
  - **Select Members**: Components of the Simulation Environment (known within DSEEP as 'members') are selected, and may vary in size from small elements to complete simulation environments in themselves. It is important to determine if pre-existing members can be reused (with the aid of a repository, if available), and to what extent they may need to be modified. Rationale for member selection should be documented.
  - **Prepare Simulation Environment Design**: The design of new members will need to be established, and the complete simulation environment design should be documented, including its overall infrastructure and selection of protocol standards.
  - **Prepare Detailed Plan**: A detailed plan for the established design is put in place. This involves updating and extending the initial SEDEP put in place in Step 1.
- **Develop Simulation Environment (Step 4)**
  - **Develop Simulation Data Exchange Model**: The information exchange data model defines how members within the simulation environment will interact with each other at runtime. This will depend, for example, upon whether an object oriented approach is being taken, or to what extent the simulation is distributed across a number of locations. The data exchange model developed should be fully documented, and must conform to the conceptual model established in Step 2.
  - **Establish Simulation Environment Agreements**: This activity is designed to ensure that all other agreements relating to interoperation are fully established before the simulation is implemented. Issues to be considered may include:
    - The need for any further software modifications to pre-existing members.
    - The need to ensure database and algorithm consistency, where appropriate.
    - Identification of definitive data sources for members and simulation environment databases.
    - Runtime management agreements, synchronisation points and initialisation procedures.
    - The definition of a save and restore strategy.
    - The definition of security procedures.
    - Data publication and subscription responsibilities.
    - Scenario instances required.
  - **Implement Member Application Designs**: During this activity, existing members are modified and member interfaces are constructed, adapted or extended as necessary. New members are implemented along with supporting databases and scenario instances.
  - **Implement Simulation Environment Infrastructure**: At this point, the required network software and hardware infrastructures are created and configured, and the facilities required to support integration and test are fully prepared. This includes availability of hardware, system administration, building air conditioning and power supply; and all other software and hardware configuration necessary. The infrastructures should be fully tested before going on to the next step.

- **Plan, Integrate and Test Simulation Environment (Step 5)**
  - **Plan Execution**: The SEDEP should be updated to take into account all the latest developments, paying particular attention to addressing V&V, test and security issues. All risks and mitigation strategies should be re-assessed, and plans for the detailed execution of the simulation fully documented.
  - **Integrate Simulation Environment**: The purpose of this task is to incorporate all members into their intended locations within the simulation environment infrastructure. Detailed progressive testing should be carried out during this process in accordance with the SEDEP, and software problems encountered should be fixed and re-tested.
  - **Test Simulation Environment**: The fully integrated simulation environment is formally tested to ensure that it can meet all its specified objectives. Test results should be reviewed with both users and sponsors, and any necessary corrective actions carried out.
- **Execute Simulation Environment and Prepare Outputs (Step 6)**
  - **Execute Simulation**: All planned simulation executions take place in accordance with the SEDEP, and all raw data outputs collected. Any problems should be documented.
  - **Prepare Simulation Environment Outputs**: Any pre-processing that is required to be carried out on the raw execution data outputs now takes place to ensure that it is in the appropriate format for subsequent analysis. This data, along with any execution problems encountered, should be reviewed to assess if there may be a need to re-run some of the simulation executions.
- **Analyse Data and Evaluate Results (Step 7)**
  - **Analyse Data**: The processed data from Step 6 is analysed using appropriate tools and methods, and results prepared for feedback to the User and Sponsor.
  - **Evaluate and Feedback Results**: The results are fed back to the User and Sponsor for evaluation, and an assessment made that the objectives of the Simulation Environment have been met. Those products developed or modified during the development process should be archived for subsequent re-use where appropriate. Lessons learned should be captured, and a final report produced.

The V&V process is an overlay over the whole of the above process, not something that is done at the end. Following the above process and learning from the experience outlined in Chapter 9 should ensure appropriate fitness for purpose and credibility, at an optimal cost and with minimum risk.

7.8.7 M&S Problems and How Best to Avoid Them

Various groups have, over the years, performed root cause analyses for problems with M&S across a wide number of domains, not just T&E. One example, given in [15] and Table 7-3, provides a typical 'Top Ten' list of reasons for M&S 'unfitness' for purpose.

Table 7-3: Top 10 Reasons for M&S 'Unfitness'.

1	People do not have enough relevant experience.
2	Evidence does not support a fitness argument.
3	Development process is wrong for the purpose.
4	Configuration management is unsuitable for the purpose.
5	Lack of recorded assumption information.
6	Data sets used in the model are inaccurate.
7	Incorrect level of modelling resolution.
8	People do not have enough training.
9	Data set is not coherent with the purpose.
10	Evidence of fitness is missing.

To elevate confidence in M&S and increase the probability of Fitness for Purpose and project success, the above can be turned into a list of recommendations. Maguire reported such a list, the QinetiQ 'Ten Commandments of M&S', see Table 7-4, and this is recommended to the reader. [15]

Table 7-4: Ten Commandments of M&S.

1	Understand the purpose of your model or simulation and re-check it often.
2	Train your people to the most appropriate level for their tasking.
3	Keep records of who did what and when.
4	Record your assumptions about reality and your model and simulation during its development.
5	Review the validity of your assumptions as development and use progresses.
6	Ensure data sets are valid, including input sets, testing sets and mathematical constants.
7	Carry out as much Validation and Verification as necessary.
8	Obtain independent checking and peer review of your work (if appropriate).
9	Collect, manage and maintain your evidence in a structured way.
10	Record system development in a Credibility Workbook.

The utility of M&S and SE to the EW T&E process can be greatly assisted by following best practice processes, such as those in the previous section, and being ever mindful of the above problem avoidance measures.

7.9 NATO MODELLING AND SIMULATION GROUP

7.9.1 Introduction

NATO RTO has a M&S Group, the NMSG, who are custodians of a wealth of information on the topic of M&S. The mission of the NMSG is to promote co-operation among Alliance bodies, NATO Member

Nations and Partners for Peace Nations to maximise the effective utilisation of M&S. They organise Symposia, Specialists Meetings, Workshops and Lecture Series on various aspects of M&S.

The interested reader is strongly recommended to visit their internet site at:

http://www.rta.nato.int/panel.asp?panel=MSG.

The remainder of this section provides top-level information on the NMSG from the above site.

7.9.2 NATO HLA Compliance Certification

The High Level Architecture (HLA) is the preferred Simulation Interoperability Standard recognised by NATO as early as 1998. HLA is an international standard as defined in IEEE and also STANAG 4603. To support proper use of HLA, the NMSG has established an HLA Compliance Certification Capability. This capability is distributed between NATO/PfP Nations and offered as a not for profit service to verify the capabilities of models and simulations relevant to being technically compliant with the HLA standard.

7.9.3 NATO Simulation Resource Library

The NATO Simulation Resource Library (NSRL) is a development tool provided by the NMSG and RTA to increase the reusability level of the simulation resources within the RTO community – registration via RTO Web Site.

7.9.4 NATO M&S Standards Sub-Group: MS3

The NMSG Sub-Group MS3 finalised the first edition of the Allied Publication entitled NATO M&S Standards Profile (NMSSP), AMSP-01. [16] This publication provides a comprehensive set of Standards that are applicable in the NATO M&S domain. The document was promulgated by the Director of NATO Standardisation Agency and is included in the NATO Standardisation Documentation Database.

The NMSSP aims to provide guidance to NATO and partner Nations, as well as national and NATO organisations who have requirements to effectively use M&S in support of NATO coalition and national requirements. It maintains information on M&S standards and recommended practices relevant to achieving M&S interoperability and re-use of M&S components, e.g., data, models. It provides a set of standards descriptions for decision making on options for the use of M&S standards for NATO activities, e.g., coalition training and experimentation.

7.10 INCREASED USE OF M&S THROUGH-LIFE

As noted in Chapter 6 and in this chapter's introduction, there is significant potential for greater use of M&S in the EW T&E process. Given the strides made to date in M&S and in the underpinning computing power increases of the last decade, this potential extends to cover the through-life case for EW and other systems. This potential for increased utility is depicted in Figure 7-5. Validated M&S, when used appropriately, can lead to reduced programme risk, schedule and cost.

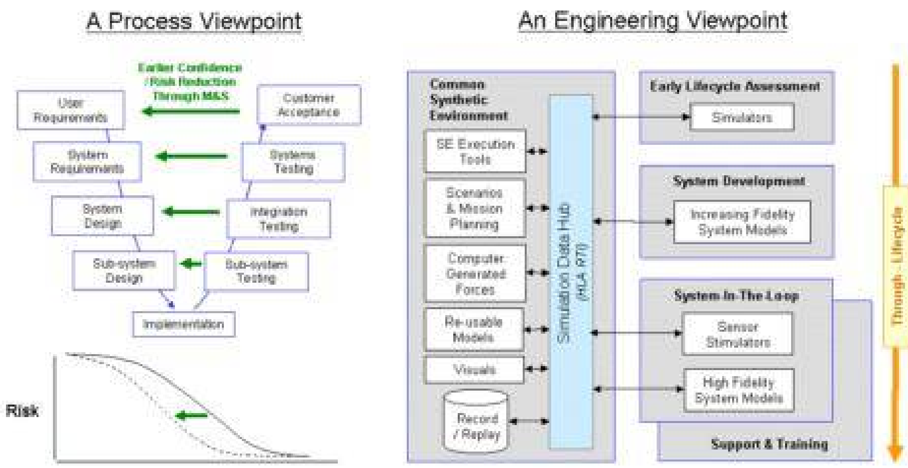

Figure 7-5: Increased Use of M&S Through-Life.

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Chapter 8 – EW FLIGHT TEST PLANNING, EXECUTION, AND OPERATIONS

8.1 INTRODUCTION

Other chapters of this Handbook addressed the technical considerations of EW T&E. This chapter deals with EW flight test execution and operations focusing on large OAR missions; however, many of the underlying principles also apply to other EW flight test operations as well as ground and laboratory testing.

EW flight test missions are complex, expensive, and frequently utilise scarce or shared resources. Disciplined test execution is necessary for test mission success. Test planning should be completed well in advance of the required need date to ensure all technical details are addressed, the required resources will be available, and test methods are applicable and sufficient to evaluate test objectives.

Flight test missions often involve coordinating the activities of multiple aircraft, threat simulators, and dozens of people in multiple locations. Each participant must understand others' roles and responsibilities, as well as their own. Data analysts must also thoroughly comprehend the data acquisition and reduction processes for each data source they will encounter.

8.2 TEST PLANNING

Sound test planning is essential to successful test execution. A test plan documents the detailed objectives, MOPs, data requirements, evaluation criteria, success criteria, test procedures, constraints and limitations. The Data Analysis Plan (DAP) details how the collected data will be reduced, processed, analysed, and used to calculate the MOPs. Detailed documentation is important to make certain that test procedures are repeatable and to smooth transitions during personnel changes.

All test plans should be reviewed by qualified engineering and aircrew personnel for technical accuracy. To aid objectivity and completeness, the reviewers should not be affiliated with the test. Test plans should also be reviewed from a safety perspective by similarly unaffiliated parties. Test plans should typically be approved at least 30 days before the first flight, although this may vary by test organisation.

The test team provides a Programme Introduction Document (PID) to the OAR. The PID describes the purpose and scope of the test programme, and documents the expected resource requirements. The test team should normally provide a PID to the OAR at least six months prior to the expected first flight. More complex efforts may require 12 months or longer lead time. The OAR will then respond to the PID with a Statement Of Capability (SOC) detailing the support the OAR can provide, as well as cost and schedule information. Close coordination between the test team and the OAR throughout the PID/SOC development process minimises risk and uncertainty, and ensures all issues and potential problems are thoroughly understood and vetted.

An important purpose of advanced coordination and planning with the OAR is to allow time for the test team to become completely familiar with the test range. Personnel must understand how the threat simulators operate, how they are instrumented, what the available data products and their sources are, and how the OAR communications systems operate.

Some common factors that must be considered in EW flight test planning are:

- **Flight Profiles** – A test plan should document the flight test profiles in such a way that the reader can understand the methodology underlying the profile, i.e., a knowledgeable reader should be able to relate the profile to the data being collected, the MOPs being calculated, and the objectives being evaluated. If the test range is known, the profile can be drawn very specifically with waypoints identified and altitudes and airspeeds specified. It is important to correctly identify tolerances for specified parameters, such as airspeed and altitude. Tolerances that are too tight reduce flexibility making execution difficult, while tolerances that are too loose risk inability to meet the objective.

- **Airspace Restrictions** – The test team needs to work with OAR personnel to tailor the test profiles to conform to airspace restrictions. Normally, airspace above the OAR's land range boundaries is restricted and can be dedicated to the test mission if required. However, test requirements frequently necessitate operations outside of restricted airspace. These operations must be coordinated well ahead of time to ensure all test requirements can be met and that objectives or procedures can be modified to accommodate any constraints. Supersonic flight operations and low altitude operations (typically below 500 feet AGL) may also require special coordination.
- **Rules of Engagement** – ROE describe how the ground-based and airborne threat simulators will operate during the test mission. Modern radar systems are extremely complicated and have a variety of operating modes and EP features. It is important to document and communicate what restrictions will be placed on threat simulator operators and the rationale for the ROE. Poorly documented and communicated ROE are a common reason for failing to meet test objectives.
- **Radio Frequency Transmission Coordination** – Radio frequency transmissions from test and support aircraft can disrupt civil and commercial communication and must be coordinated with the OAR's frequency managers. The frequency spectrum and type of transmissions such as noise or false target EA techniques must be identified. Some types of transmissions may generate geographic, altitude, or time-of-day restrictions.
- **Expendable Countermeasures (EXCM) Separation** – EXCM such as chaff, flares, and towed decoys require advanced coordination. Chaff is designed to disrupt hostile radars and can also affect civilian air traffic control radars. Chaff clouds can persist for a long time and can also be carried by the wind. Flares pose a fire hazard when dispensed at low altitude. Towed decoys typically weigh several pounds and can pose a risk to ground-based personnel and facilities if an inadvertent separation occurs. Test planning must consider where the towed decoy operations will occur to avoid over-flying manned sites or high value assets.
- **Support Aircraft** – Several types of support aircraft are often employed in EW testing. Airborne threat surrogates function similarly to ground-based threat simulators by resembling hostile airborne weapons systems. Safety chase aircraft may be required for some operations, particularly those involving EXCM separation for new systems. Specialised aircraft can perform signature and other measurements of the test aircraft, such as IR radiometric measurements. Refuelling tankers can increase test efficiency by extending a test aircraft's time on range.
- **Data Products** – Early coordination with OAR data analysts can greatly reduce post-mission data analysis turnaround times. Early coordination ensures that the test team's data analysis tools are compatible with the OAR data products, either by specifying data format requirements with the OAR or by modifying the analysis tools to make them compatible. Processing sample data products from the OAR before testing begins is an excellent risk mitigation procedure.

8.3 FLIGHT TEST EXECUTION

Successful EW T&E test mission execution on OARs requires the disciplined, concerted efforts of numerous people in multiple locations. Accurate and concise documentation for all participants is essential to effective test mission execution. Test planners must understand the roles and responsibilities of the various participants to ensure efficient and effective test execution.

8.3.1 Mission Execution Documentation

The test plan and DAP provide a comprehensive description of the overall test effort. A sufficiently detailed test plan supports the creation of flight and test mission cards that are thorough, yet concise, organised, and targeted to specific readers. The importance of well-written flight and test mission cards cannot be overstated, as they can mean the difference between mission success and failure.

Flight cards provide aircrews with all of the necessary information about each test point. At a minimum flight cards should contain:

- OAR entry and exit procedures;
- Radio frequencies and call signs;
- Test point numbers;
- Test profile diagrams with waypoints and airspace limitations;
- Altitudes and airspeeds with tolerances;
- Manoeuvre information; and
- SUT configuration details and operating procedures.

Pilots and other aircrew members operate in a high-workload environment and in tight quarters; they need complete information formatted for the quickest reading. Superfluous details, extraneous words and inconsistent styles can cause delays or confusion with detrimental results. During a typical RWR test, for example, the test conductor, SUT analysts, and threat simulator radar operators must know the threat simulator modes, such as frequency, PRI, or scan type. This information is generally unnecessary to the pilot and therefore should be omitted from flight cards.

The Test Director (TD), Test Conductor (TC), system analysts, and threat system operators should have mission cards containing the details required to execute each test point. Events happen quickly in a flight test mission. Just as with flight cards, mission cards should be succinct, well-organised and contain only vital information. For a given test point, the threat simulator operators need to know the ROE for target engagement and how to configure their radars so this information should be included on their mission cards. If they do not need to know how the SUT is configured, then SUT configuration details should not be on their mission cards.

Additional SUT and flight test documentation such as the test plan, safety procedures, flight manuals, etc., should be available in the mission control room for SUT troubleshooting or emergencies.

8.3.2 Test Mission Participants and Conduct

Figure 8-1 illustrates the participants and their interaction in a typical EW OAR flight test.

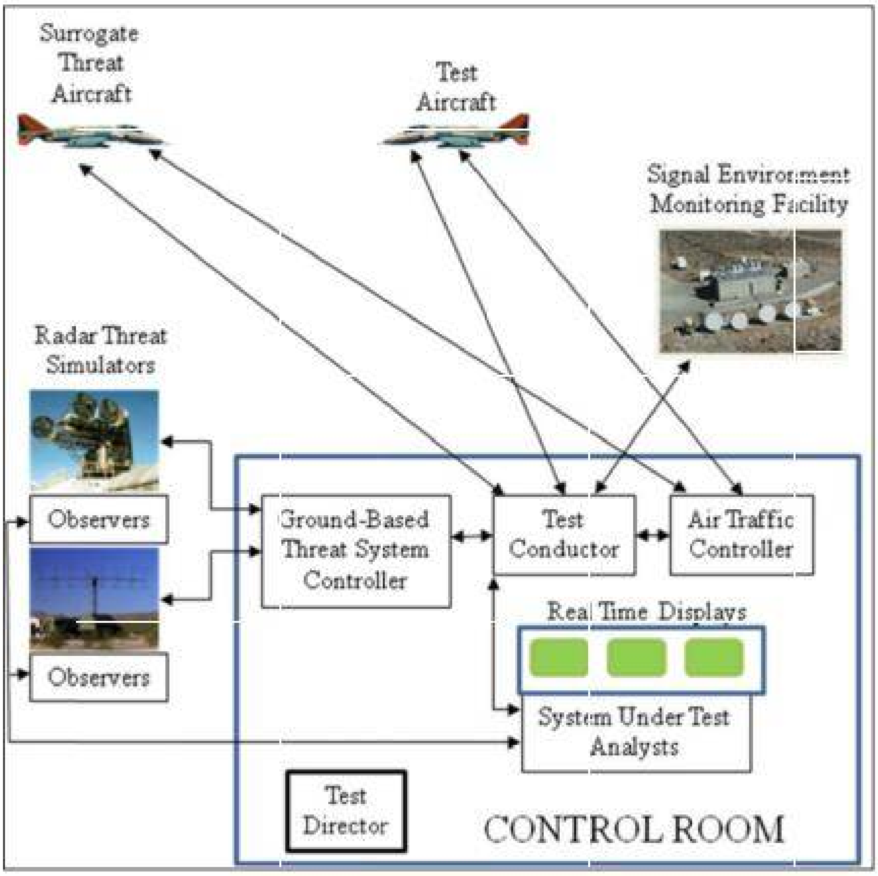


Figure 8-1: Typical EW OAR Mission Participants.

- **Test Director** – The TD has overall responsibility for a test mission. The TD is ultimately responsible for safe and efficient mission execution and generally does not get involved in the details of the test point-by-test point conduct of a test mission. The TD must maintain a separation from the mission details to ensure the mission is conducted safely and avoid becoming fixated on the mission details and losing overall perspective. The TD needs to have substantial aircraft and sub-systems knowledge to assist the aircrew in the event of an emergency. The TD also makes real-time decisions when there are planned or unplanned mission changes that could affect mission success or test point completion.
- **Test Conductor** – The TC coordinates the step-by-step execution of each test point as documented on the test cards. For safety reasons, the TC has limited discretion to deviate from the approved test procedures documented on the test cards. The TC ensures that all active participants (the test aircrew and air traffic controllers, threat system controllers, and analysts) are ready to perform the

duties associated with the current test plan. In test missions with multi-position aircraft, particularly those with complex EW suites, an airborne test conductor can coordinate the activity within the aircraft. However, an airborne TC should always take mission direction from the TC in the control room, who will always have the most complete knowledge of the overall mission situation, particularly the operational status of the threat simulator systems and their availability to participate on a given test point.

- **SUT Analysts** – The engineers and analysts are experts on the SUT and its performance. They monitor the real-time SUT data as well as data from the threat simulator systems. When the SUT is not operating as expected, these experts advise the TD and the TC regarding how or whether the mission should continue.
- **Ground-Based Threat System Controller** – The ground-based threat system controller communicates the details of each test point to the threat simulator operators who will be participating on a given test point. Typical information details include frequencies, PRIs, modes, and ROE. The ground-based threat system controller also communicates information about threat system maintenance status to the TC and the system analysts, which allows them to react to changes in threat system availability.
- **Air Traffic Controller** – The air traffic controller directs the activity of airborne assets including test aircraft carrying the SUT (or SUTs) and surrogate threat aircraft. The air traffic controller also coordinates the test aircraft range entry and egress process, and handles other air space coordination issues.
- **Test Aircraft Aircrew** – The aircrew fly the test aircraft and operate the SUT(s) and onboard instrumentation. They operate under the direction of the TC and/or the air traffic controller. In multi-crew member aircraft, mission support aircrew can monitor onboard instrumentation systems and provide additional information to system analysts in the control room beyond what telemetry data provide.
- **Test Support Aircrew** – The test support aircrew operate airborne threat surrogate aircraft or airborne measurement aircraft under the direction of the TC and/or the air traffic controller.
- **Signal Environment Monitoring Facility** – The signal environment monitoring facility provides an important resource to analysts during the mission. The facility can monitor threat simulator outputs and the transmissions generated by the SUT(s), including ECM signals. It also monitors the environment for signals that are not part of the test setup, as extraneous signals can interfere with the performance of the SUT.
- **Threat System Observers** – The threat system observers supply information about the effectiveness of a given ECM technique. Many ECM techniques are visually subtle; a knowledgeable observer at a threat site with the radar operators can be an invaluable source of information. Observers need to be familiar with the specific threat system they will be observing, as well as the ECM technique design and its intended effect(s).

8.4 OAR DATA COLLECTION

The purpose of a flight test is to collect data, which is used to calculate MOPs for test objective evaluation. The flight test team must understand what data are available and how the data will be obtained and processed. Figure 8-2 illustrates the various data sources and how they are collected.

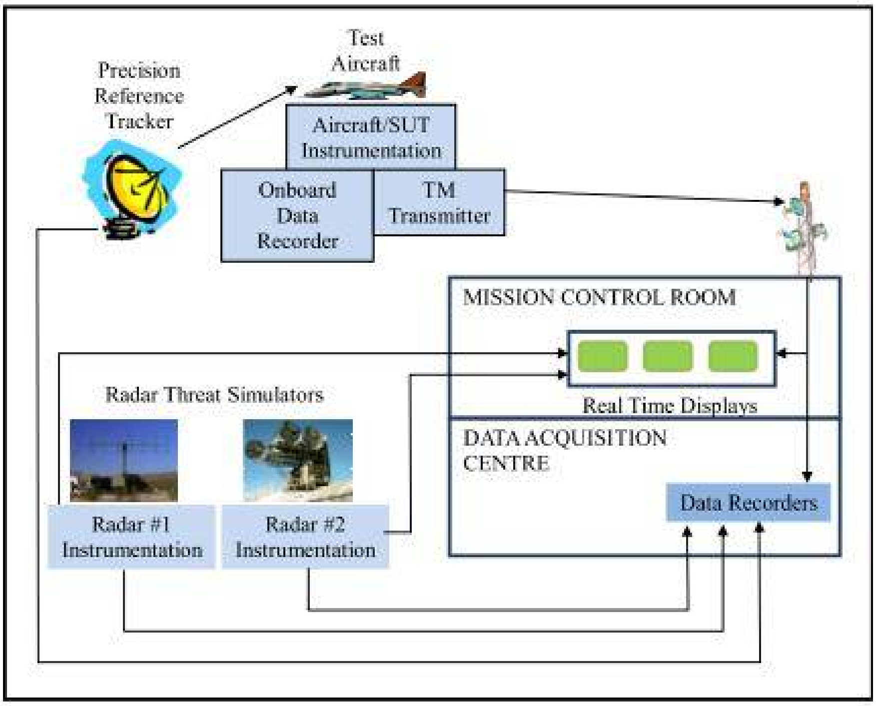


Figure 8-2: EW OAR Test Mission Data Sources and Routing.

There are three primary points of data collection:

- **Test Aircraft** – The SUT(s) will generally have onboard data recorders to capture, store and transmit time-encoded critical test data. Certain aircraft parameters, such as position and attitude, are frequently recorded as well. Modern data recorders are normally solid state devices, although magnetic tape recorders are still common. Video capture devices record the aircraft displays, directly where possible. Telemetry (TM) allows selected critical parameters to be transmitted from the test aircraft for real-time processing and display to analysts in the control room. TM provides analysts with instantaneous data to determine if the system under test is operating as expected.
- **Threat Simulator** – Instrumentation is largely system specific, and should be researched and understood by the data analysts. Common parameters are: system on time, system off time, operating frequency, PRI, and EP modes. These parameters are commonly extracted from the system, time encoded and transmitted to a data acquisition centre where they are recorded. The OAR personnel will normally work with customers to provide data in customer-specified formats and media. During flight testing, video and certain parameters can be extracted and provided to SUT analysts in the control room to support real-time analysis.
- **Precision Reference Tracker** – Precision reference radar trackers are less important than they were in the past due to the increasing availability of GPS-based TSPI sources, although they still are generally available and have applications. A variety of radar types provide TSPI for aircraft. Each OAR can provide information about the radar types they employ. Radar beacon transponders can greatly enhance TSPI radar accuracy.

Chapter 9 – LEARNING FROM EXPERIENCE

9.1 INTRODUCTION

This chapter gives examples of problems encountered during T&E of EW and related avionics systems over more than three decades. For each problem a root cause analysis enabled identification of one or more learning points. With the benefit of experience, most problems that were noted are now avoidable. The EW T&E practitioner wastes less time, effort and money by anticipating and avoiding past problems. This improved efficiency is essential to the T&E process, particularly in an uncertain economic environment.

9.2 BACKGROUND AND OTHER SOURCES OF LESSONS LEARNED

Berkowitz, in his paper *EW Testing Lessons Learned,* summarised points with which the authors of this updated AGARDograph fully concur:

> 'Electronic Warfare testing provides many challenges and is fraught with dangerous problems. Fortunately, many problems can be anticipated and avoided. [The] secret to EW testing is "Plan, Plan, Plan ..." Yet despite the best laid plans, there will be problems ... that is guaranteed. However, with foresight and planning, at least they won't be the same old familiar problems.' [1]

This chapter, in common with similar 'lessons learned' publications, actually gives 'lessons identified' – better described as 'learning points' – rather than 'lessons learned'. A lesson cannot accurately be described as 'learned' until the required action is taken to prevent the problem's recurrence. This subtle distinction is important to note; unfortunately, experience has shown that it is difficult to achieve lessons learned.

Against this background, this chapter aims to provide novice, experienced and expert EW T&E engineers and programme managers with problem recurrence prevention knowledge to help minimise cost, time, effort and risk on future EW trials on all types of T&E facilities. This knowledge has been gleaned from many contributors, who together have hundreds of years of T&E experience on a multitude of EW systems, on many platform types, and in a number of NATO Nations.

The examples that follow have been collected directly from test engineers in the field. They provide useful insight to the types of failures or anomalies that have been frequently experienced in the course of testing. While some examples are very specific and might seem too unique to be of any help, they are presented here to illustrate the broad range of problems that may occur.

Further examples of learning points are contained in Berkowitz's *EW Testing Lessons Learned* and Stadler's *Test and Evaluation Lessons Learned from the Field.* Although these examples are not repeated in this chapter, they contain much useful information for the EW programme manager, test planner and test engineer alike, and their study is recommended. [1],[2]

Readers are invited to add to this knowledge base, for inclusion in this Handbook's next update, by contributing EW T&E lessons learned. Contact information can be found on Page xxvii.

9.3 LEARNING POINTS IDENTIFIED

The following notes apply to the lessons and learning points identified in this chapter.

- All lessons identified in this chapter are offered by the contributors without prejudice, liability or commitment. They are provided in good faith to help reduce the time, cost and risk of EW T&E across NATO and its partner Nations.

- The learning points:
  - Are presented in no particular order or priority.
  - Supplement the commentary within Chapter 6 on the strengths and limitations of various types of T&E facilities.
  - Have had most references to specific programmes, projects, platforms, equipment and persons removed.
- The problems and learning points resulted from T&E at various stages of the SUT life cycle, from R&D through D&D to DT&E/OT&E and in-service use. They have resulted from T&E of EW equipment in isolation, from sub-system (Defensive Aids Suite) integration activities, and from systems integration activities and platform-level T&E on the ground and in flight.
- Most lessons, although originating from air platform EW T&E, are considered equally applicable to EW T&E for land and sea platforms.
- Many learning points identified yield suggestions to the EW SUT and air platform specifiers and designers on how to ensure repetition of the problem is prevented.

Table 9-1: Lessons Learned – An Aid to Problem Recurrence Prevention.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Know the expected results	During planning for tests, you should identify the expected test results so any differences are readily recognised and, if necessary, more data can be taken. Generally, it is too late after tests are conducted and data are analysed to try to get additional information about a failure. It is good to prepare blank data sheets ahead of time and perhaps make a mental or dry run, as may have been done during college physics laboratory, so critical laboratory test time and/or assets are not wasted. An example is given below. When out-of-band frequency measurements were made on a jammer's transmission signal, spurious signals at low frequencies with powers exceeding those allowed by the specification were detected. These measurements were discounted since only very low level signals were expected because the band being measured had a waveguide output, which acted as an excellent high pass filter. The tests were repeated with a Low Pass Filter (LPF) inserted, and the spurious signals disappeared. The LPF attenuated the strong in-band signal which was saturating the spectrum analyser. If the expected results were not postulated, extensive measurements would have been recorded on the phantom signals and it may have been erroneously reported that the jammer design didn't meet specification. Whilst applicable to most avionics T&E, this risk of wasted time and effort is especially so for EW systems, in particular for RWR/ESM-to jammer tests, where the final test result is often not known until post-test analysis has been completed. A problem discovered then often means a full re-run of the test and analysis.	Test time and effort can be wasted if the tester does not have a good idea of what the test result should be. Two items are particularly helpful in reducing T&E time, cost and risk: • Pre-test prediction of acceptable results. • Use of Quick Look-See features in test equipment, e.g., QLS in the Northrop Grumman Amherst Systems' ECM Signal Measurement System. This allows problems to be picked up at the time of the test, enabling further and/or investigative measurements to be quickly taken.
Know and understand Interface Control Documents	The root cause of a number of problems encountered during EW T&E have been attributed ICDs. Problem recurrence could be prevented if the following clarifications were added to ICDs: • Tolerances on leading/trailing edges and widths of digital pulses, especially on blanker (suppression management) systems. • Precise specification of connector type, shell orientation and pins/sockets for equipment and aircraft connector. • Precise identification marking on aircraft connectors/cables and equipment boxes.	Test engineers need not only to have an intimate knowledge of the specification of the EW SUT(s) they are about to test, but also they need to know and understand the ICD(s) that govern the interconnectivity between the SUT(s) and other avionic and other equipment to which it connects.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Know and understand Interface Control Documents (cont'd)	• Expansion/clarification to prevent problems that cannot be attributed to either ICD or specifications. • Formal review of ICDs are required whenever equipments are modified. Unplanned investigation and solution costs and time delays have been incurred where this has not been done. • Although it has been suggested that equipment specifications be refined to include a better definition of the on-board and external RF environment, there is a case to include this in ICDs. That is, treat the airframe and surrounding atmosphere as an 'interface' between RF transmitters and receivers.	

Aircraft ground trials problems resolved by use of anechoic chamber facilities	Most problems encountered on aircraft ground test on outside test sites can be prevented or mitigated by running those trials in the weather- and electromagnetically secure environment within anechoic chamber test facilities. Generic problems encountered that can benefit in this way include:
	• RF pollution/interference/security clearance for transmissions, with severe restrictions on the use of frequency agility and 'war' modes: severely limits scope, time and location of tests.
	• Weather limitations: Between technical (design and operation), natural (weather, environment and limited number of daylight hours) and logistical requirements (need for opening radome, bays and canopy) during such trials, a general observation by Trials Managers has been made that outdoor EW trials in winter should be avoided if possible. Investigations by one PSI have shown that over 15% of aircraft EW ground test programme time was typically lost to weather alone.
	• Reflections, especially from wet ground and nearby metalwork on radars/radios/ECM/RWR/ESM trials:
	  • Microwave and millimetre wave propagation is dependent on atmospheric conditions.
	  • Multi-path effects and the very low grazing angles used with respect to the ground lead to distortion of results and a wholly unrealistic external environment around the aircraft, in many cases leading to problems seen on the ground but not repeatable in flight et vice versa.
		• Avoid executing aircraft ground trials on open air test sites during the winter months, to optimise test programme schedule, risk and cost.
		• Use anechoic chamber test facilities in preference to outside test sites for aircraft EW ground trials. This will aid minimise time and risk, and maximise the scope of tests possible.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Aircraft ground trials problems resolved by use of anechoic chamber facilities (cont'd)	• Furthermore, the uncontrolled nature of these reflective surfaces makes repeatability of test results almost impossible to attain. This is seen as the dominant factor in the overall poor quality of EW test results other than those in anechoic chambers and has led to the need for much repeat on-aircraft test work. • In many EW receiver cases much test effort has been wasted as a result of using an uncontrolled RF environment. Only an anechoic chamber can provide a suitably controlled environment.	
EW flight trials problems	A number of generic EW T&E problems have been noted during flight trials, some of which are similar to those noted in this table regarding ground trials: • Weather: The impact on trials duration is generally worse that that noted above on ground trials. • Limited number of EW test ranges, and the limited RF emitter scenarios that can be generated (see also Chapter 6). • Logistical difficulties and cost of using airborne EW targets. • Security clearance for use of sensitive ECM/radar modes. • Poor instrumentation of EW systems. • Poorly documented and communicated Rules of Engagement for the operation of ground-based and airborne threat simulators during the test mission. One of the most common reasons for failing to meet test objectives.	• Wherever possible, move EW DT&E/ OT&E work from flight to ground test, in anechoic chamber ISTFs, laboratories and via the use of suitably validated M&S. • To minimise cost and time, limit EW flight test to those areas that can only be cleared by flight test.
Test engineer experience	A prior study showed the importance of having capable, experienced test engineers with a good appreciation of the 'real world' that the EW SUT is required and designed to work in. There is also a clear need for a 'wide-eyed' approach to rig testing. Here emphasis needs to be placed, within financial constraints, on examining system performance against the 'real world', rather than merely testing word for word against the requirements of the equipment specification. The benefits of using such engineers with that approach was seen by comparing the EW problem-finding ratio SIL-to-flight test for one platform variant vs. that of a different variant of the same	Use experienced RF and EW test engineers if a minimum risk, cost and duration rig and aircraft trials are required.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Test engineer experience (cont'd)	platform. The SIL with the experienced RF and EW engineers found four times as many problems than the lesser experienced team on the second SIL, resulting in many less problems being left to be found during flight trials. The study also showed that there is a definite requirement for feed-forward of SIL test expertise to aircraft ground and flight test, in the form of systems 'specialists' who move with the SUT through its development life cycle. Failure to do this resulted in a large number of problems being re-found, re-investigated and re-raised as problem reports during the aircraft ground and flight test phases.	
Importance of formally reporting problems	Formal system/avionic problem reports are part of a closed-loop process that ensures problem fixes or adequate and acceptable explanations result. Unfortunately, these reports have not always been raised during EW/avionic trials on rigs, during aircraft ground test and flight test. Sometimes this has allowed real problem to get past DT&E and OT&E only to be then be reported from operational use by the air force(s) concerned. Some have even had adverse operational impact. The reasons for this are varied, with some examples here: • Test engineers do not recognise there is actually a problem present. This is most usually caused by either unfamiliarity with the SUT and its specification (see separate 'Know your SUT' lesson) or inexperience or a combination of these. • The problem is 'covered' in the test report for the trial concerned, but has then lain dormant and un-progressed for a considerable period of time or not followed up at all. • Reluctance to report problems from aircraft ground and flight test for fear of slowing, lengthening or having to stop the trial. • The view of some engineers that if a problem cannot be repeated it is therefore not a problem – see separate lesson learned on this topic. • Test engineer enthusiasm to "get on with testing".	• Always raise system/avionic problems when something does not or does not appear to operate correctly. It will never get fixed if you don't report it! • Even if the SUT meets its specification, if – as a professional engineer – you believe there is a problem that will adversely affect its successful operation by the end user, then raise a problem report. • In this way there can be a reasoned examination of whether the specification itself may have shortfalls or ambiguities – a common occurrence. • At best you will have prevented a problem being passed to the platform's operational phase and optimised the time and cost of fixing it; at worst you will have spent a relatively small amount of time getting clarification of what the SUT should and should not do.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
RF threat simulation capability and use	Many problems encountered during T&E of EW receiver systems (RWR/ESM/ECM) have been traced to inadequacy of, or problems with the use of RF threat simulators. Points of note are: • Test engineers should check that emitter data programmed into the threat simulator is compatible with that programmed into Mission Data in the EW SUT. Much time has been wasted due to data/database errors and differences between these or between one or both of these and the parameters of the real threat emitter. • To maximise the potential for conducting as much of RF EW system testing on sub-system and systems integration rigs rather than on aircraft, a fairly substantial RF threat simulation capability is required. The 'rule of thumb' 1.0 Mega-Pulses Per Second capability, whilst adequate for testing some RWR systems, is considered less than adequate for modern ESM. • Unless the threat simulator has intra-pulse high fidelity modulation (pulse shaping) capability, the test engineer should remember that simulators generate signals that can have considerable differences to the real-world emitters they are simulating. Consequently, EW SUTs may react differently in the rig/chamber environment to how they will on an open air range against a real threat emitter. • Emitter and scenario construction and validation prior to use in T&E is complex and can be prone to human error. Appropriately thorough checking is essential to prevent problems. The use of emitter validation tools such as the Northrop Grumman Amherst Systems Inc. Environment Graphical Analysis (EGA) tool can help the test engineer visualise what is happening in the scenario with time and does not tie up the threat simulator whilst the emitter and scenario construction and validation takes place. Such tools also allow the T&E engineer to double check that the test scenario being constructed can actually be catered for by the digital and RF resources of the threat simulator. Without this level of care in the construction and use of threat simulators it can be very difficult to see, investigate and resolve a problem. Indeed, it is wise, when using complex RF scenarios, to examine both the SUT and the test set-up when a problem is first encountered.	T&E engineers need to understand the capabilities and limitations of the RF and other threat simulators they use. These are highly specialised items of test equipment and specialist advice should be sought as necessary.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
On-board and external RF environment	Some of the more subtle, problematic and operationally serious problems encountered concern the performance of RF EW systems when exposed to the on-board and/or external RF environments, including the formation flying case. This item can be broken down into two aspects: • EMC of the EW systems themselves: To assure problem-free operation the EMC specification of the EW equipment must adequately cover the operational air RF environment the platform has to operate in. This is not always adequately covered by standard EMC qualification tests and unexpected problems have been experienced during aircraft ground and flight test. • The performance of RWR/ESM/ECM systems in the presence of a given external RF environment: In this case, receiver front-end overload has been seen on a number of occasions. How this manifests itself and the immediate and subsequent warnings to aircrew of system performance degradation have been the subject of a number of problem reports.	• Develop an accurate definition of the operational air RF environment the SUT has to operate in. This needs to include formation flying aircraft RF emitters, the on-board RF environment, reflections of own emitters from the ground and other aircraft, surface/sea emitters and other airborne RF sources. • Use M&S tools to develop robust predictions of this environment where measured power density profiles are not available. • Provide the RF EW equipment supplier with an accurate picture of the total air RF environment.
RF inter-operability, antenna coupling and RF compatibility	Confusion about the specific meaning of the terms 'RF Interoperability' and 'RF compatibility' in aircraft EW ground trials has led to duplication of on-aircraft test work under the guise of first EW performance verification, and then EMC clearance of platform. Whilst the definitions vary across Nations and their agencies, a common view is: • **Interoperability tests** involve the EW systems' antennas with the receivers and the rest of the RF EW system connected. It addresses how RWR/ESM/ECM equipments perform when subjected to the actual RF environment generated by one or a combination of other transmitters on the host aircraft. Encompassed in this is demonstration of adequate RF suppression management to ensure that RWR/ESM/ECM systems can perform their respective tasks adequately. • **Antenna coupling**, which has by far been one of the biggest problem areas during EW systems integration on military air platforms, is a function of the transmit/receive antennas, their installation, the airframe and the RF power density generated by each transmitting antenna.	Ensure an all-party understanding exists of these terms at the outset and thus tailor test programme to minimise duplication.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
RF inter-operability, antenna coupling and RF compatibility (cont'd)	It involves the determination of installed antenna polar diagrams and the quantification of energy coupling between antennas or groups of antennas anywhere on the aircraft. This coupling is to be determined for all stores configurations to be used, especially where large reflective surfaces are added, e.g., external fuel tanks. The coupling can be measured by connecting a suitable RF signal generator/amplifier to the transmitting antenna and a spectrum analyser to the receiving antenna. Antenna coupling is essentially an EMC test and numerous examples have been seen over the years. Antenna coupling power measurements can be used by EW/radar/radio equipment manufacturers to optimise receiver performance and suppression management strategies. • **RF Compatibility Matrix demonstration** is an EMC test and comprises the operation of each aircraft transmitter singly and in combination, whilst monitoring for any interference caused to the aircraft's receivers.	
RF inter-operability of installed radar and RWR	When carrying out flight testing shortly before a new RWR capability was due to be cleared for operational use, it was found that when the FCR was in certain frequency agile modes, the RWR intermittently displayed false threats at around 7 o'clock. The Government Customer had placed 3 separate contracts for the systems involved: • Government Furnished Equipment (GFE) contract for the radar from a system supplier. • GFE contract for the RWR from a different division of the same system supplier. • System installation by the fighter aircraft company. For "need to know" reasons, the engineers in the aircraft company and in the RWR division had not been given the details of certain FCR modes. When the problem was pinpointed to the interaction between the FCR and the RWR, the Customer was frustrated that none of the 3 companies/divisions involved would accept liability (i.e., pay for) fixing the problem, despite high level pressure from the Customer. Owing to operational urgency, the RWR was accepted for entry to service with a known problem that took a considerable amount of time and effort (commercial and engineering) to fix retrospectively.	• Ensure that someone has clear contractual responsibility for platform system integration, including RF Interoperability. • Ensure that the engineers involved in designing and testing the RF Interoperability of the installed systems are recognised as having a "need to know" for the detailed transmit characteristics of all of the radar modes to be used operationally. • Conduct installed RF interoperability testing of classified modes in an anechoic chamber as early as practical in the project.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Ensure EW SUT serviceability prior to test commencement	Always run a complete I-level repair test on the SUT (including sensitivity and power levels) before it is tested on an aircraft, and repeat the diagnostic after taking aircraft data. If a SUT fails part of the second I-level test, it may explain why that SUT failed aircraft tests. For example, an RWR missed identifying emitters in a certain quadrant during an operational test. After repeating an I-level test, it was later determined that a hardware failure had occurred and there was not a design deficiency with the RWR.	Use appropriate processes to ensure that the SUT is fully serviceable prior to commencement of testing.
Where are the problems in an EW equipment likely to be?	It is rare that a completely new EW or other technology is introduced to a platform. Consequently, in general terms, another test engineer, somewhere in the world has already 'walked the path' that you are about to walk when designing an EW SUT or planning and conducting T&E on that EW SUT on a particular platform. Despite this, international experience has shown that many engineers, of all disciplines, have appeared to think that they were the first to design, install, integrate, rig-test, aircraft ground/flight test an equipment of a particular genre, e.g., a radar, a flare/chaff dispensing system, a RWR. SUT designs and test plans have been generated from scratch and few, if any lessons have been learned. In this way many problems and inefficiencies have been re-encountered project after project, within and across Nations. It is beneficial and relatively easy to investigate what problems have been encountered on prior projects introducing or upgrading EW systems on platforms. These problems comprise problems with the SUT itself and T&E problems. For example, understanding where problems are most likely exist on a new towed RF decoy by investigating where problems occurred on prior TRDs, and with the T&E of those TRDs enables: • Problem prevention (by SUT/platform design or modification); and • Tailoring, focusing and optimising of T&E philosophy and methodology, procedure and facilities.	Focus the T&E plan by: • Investigating what problems were experienced by others when testing an EW equipment of the type and/or genre you are about to test. • Wherever possible, talk face-to-face with the designers and testers of the prior systems. • If accessible, use prior problem reports on a given EW equipment type to indicate where problems might be. • At the start of a new project, a run-through of all previous problem reports (closed or otherwise) for EW equipment of a similar genre is highly likely to save considerable time and effort in the overall T&E programme.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Verification via 'read across'	Function and performance verification of a project's deliverables was managed via Specification Verification Matrices, which used the generic verification evidence classes: Inspection, Analysis, Test and Demonstration. This project benefited greatly from realising the opportunity of read across of relevant verification evidence from prior projects, reducing both overall project cost and risk. Some read across was defined/assumed at project outset and more was identified and realised via the risk and opportunity management process. Two issues were encountered that, with hindsight, could have been prevented: • Some verification evidence from a prior project was found to have been incomplete and/or incorrect. This project's Factory Acceptance Test process and procedure trapped these few issues. • Adequacy of prior project testing for read across: On one major deliverable it was assumed that the recent prior project had adequately checked out their almost identical deliverable. This proved not to be the case and significantly more testing and problem investigation was required than anticipated, adding considerable risk and duration to this project.	• Minimise project cost and schedule via identification of maximum read across of verification evidence at project outset. • Ensure all read across evidence is appropriately reviewed prior to use, especially items in the 'Test' and 'Analyses' verification categories. • Continually watch out for further read across opportunities, as it is generally easy to realise the cost / time / risk benefits.
Don't forget multi-path!	During the development phase of a RWR it was thoroughly tested using an open-loop radar environment simulator in a HITL laboratory. The RWR utilised a four-port amplitude comparison system, and the antenna pattern values measured from actual antennas tested at an antenna measurement facility were programmed into the simulator as a function of angle and frequency. Dynamic test scenarios were developed to exercise the system to its specification limits. The test scenarios were put into a digital model that predicted the display for the entire 6 minute scenario. The system was designed to only look for six different kinds of threats. Threat frequency ranges and scan and PRI values were varied over the radar limits. When the display presented something different than the digital model, the contractor was allowed to change the system algorithms until the system was optimised. This took 3 weeks of extensive laboratory test time. The system software was then "frozen" and parametric data were recorded on the capability of the RWR.	• Create ground and inter-platform multi-path representative of the planned flight trajectory during SIL/HITL testing by coupling a sample of the signal with the anticipated delay and reflection/diffraction loss. Adding random amplitude and phase modulations increases the fidelity of the multi-path simulation. • Be mindful that, especially for aircraft ground tests, RF energy reflections around the aircraft itself can substantially change test results when compared to anechoic chamber and SIL/HITL trials.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Don't forget multi-path! (cont'd)	When the system left the laboratory everyone felt the system would perform outstanding during flight test. However, during the first flight when only one threat was radiating, the RWR displayed two and sometimes three symbols at greatly varying angles and ranges! After analysis it was determined that the radar signals were not only going directly into the antenna to be processed but the antennas were receiving the signal reflected off various parts of the aircraft body. The antennas were receiving the same signal from multiple paths! Since the signals were received at slightly different times and amplitudes, the system processed them as separate signals. A great deal of time and money was spent fixing the algorithms to correlate the signals to a single emitter.	• The aircraft's stores configuration, including fuel tanks, weapons, jammer pods, etc., significantly alters the number of reflective surfaces involved. Reflection/diffraction in some cases is further complicated by the non-metallic materials some stores are made from. • Computation Electromagnetic Modelling can help predict test results and investigate any problems encountered. CEM can also assist in clearing EW SUT performance against different stores configurations – aircraft test programme durations and budgets usually prohibit EW SUT testing for every stores and aircraft configuration.
M&S credibility and fitness for purpose	Problems encountered are discussed in Chapter 7, Section 7.8.7.	See Section 7.8.7.
The high value of video recording during aircraft and rig trials	The lack of suitable video recording of EW system and other displays during rig and aircraft ground/flight trials has hampered many trials over the years and made investigation of some of the trickiest problems encountered difficult and time-consuming. Video recording is a well-established diagnostic tool. Where it has been available and been used, it has helped test engineers quickly home in on the root cause of problems and has aided the identification of solution options.	Always consider the use of video recording of key aircraft displays during EW ground and flight trials.

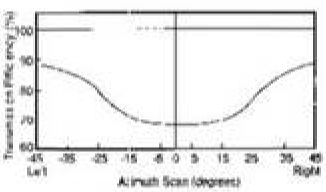
TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Simulation vs. Stimulation of RF EW SUTs	The simulation/stimulation issue is important to EW, radio and radar systems. The [Platform A] EW SIL experience has shown that most of the RF interface problems that could have been found on the rig using the techniques and test equipment available in fact were found. The bulk of this work was done by low power irradiation of receiver antennas, with a lesser amount of direct, cable-connected transmitter to receiver injection of RF signals. Although some investigation was conducted into direct signal injection at Intermediate Frequencies it was decided that the End-to-End concept should apply – i.e., test the system out as it would be in the aircraft. This investigation has shown that the end-to-end concept is robust for EW systems, with some confidence that many of the RF interface problems would have got through to aircraft had it not been for this approach. There has been a marked reluctance to consider the use of SILs in this area, probably stemming from an incomplete understanding of the power of the rigs as investigative and diagnostic tools for RF problems. For example, the [Platform C] radar-RWR interoperability problem entailed extensive aircraft ground/flight trials for some three years. Although it is accepted that airframe effects could only have been examined on aircraft, it is believed that most of the optimisation of RF 'windows' in the RWR could have been carried out using a real radar on the [Platform C] SIL. Thus it is concluded that much time and effort could have been saved in this area.	Use real RF systems on SILs and in anechoic chambers to: • Minimise RF interface problems getting to aircraft trials. • Cost-effectively investigate and diagnose RF interface problems.
Bypassing a platform's SIL causes problems	As a result of deliberately bypassing tests on a platform's SIL, problems that could have been discovered on that SIL have subsequently been discovered during EW on-aircraft trials, resulting in a higher cost-to-find and cost-to-fix. In three cases this occurred on the EW systems of [Platforms A and B]: ECM, blanker (RF suppression management unit) and CMDS. The reasons are varied why this problematic short-cut was taken in each case. Some aspects include: • SUT cleared for aircraft on the basis of tests with the manufacturer's test set only. • Prior testing, done years before on a much earlier variant of same platform type, was done by "trial and error". In retrospect the trials manager concerned described the earlier results as "totally wrong". • Failure to recognise that SILs have a powerful role to play in RF system testing.	New or upgraded EW equipments, or those previously fitted to other platforms/variants, should not be introduced to an aircraft type without going through normal system integration tests in the SIL for that type.

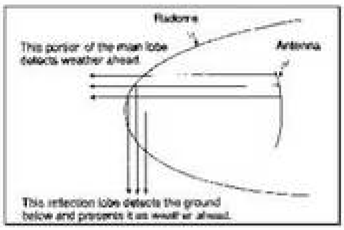
TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Set time limits on troubleshooting	When a problem is encountered during part of a test, set a prudent amount of time to investigate, then continue the original test procedure because if the initial problem cannot be readily understood, subsequent testing and results may provide a clearer understanding or solution of the original problem. As an example, weeks were spent trying to uncover a problem which was caused by an avionics system contractor tying one side of a multiplex bus to a pin labelled 'no connection' at the systems, and the airframer grounding the wire going to the 'no connection' pin at the airframe end. When the cable was attached to both connectors, the bus was being shorted to ground. All testing was stopped until the problem was found. It would have been better to have spent a day or so, then continue with the original tests, and try to solve the problems in parallel.	To maximise test timescale success probability, especially on aircraft ground trials: • Set a limited time for investigation of a problem after encountering it, prior to returning to execute the next test in the planned sequence. A rule of thumb is up to 4 hours. • Conduct further investigation of problems discovered during a test sequence once the entire planned sequence has been completed.
Understand timing relationships, measurements, and uncertainty	Data analysts must understand what is being measured as well as the precision and accuracy of the measurement. Response time is a common measure of performance in EW RF receiver testing and makes a good example. The response time calculation requires the analyst to know the initial time, i.e., when the radar began to transmit and the time when the event of interest occurred, e.g., the RWR displayed the related symbol. The OAR post-mission test data will include the "ON" times for the subject radar. Analysts must understand exactly what this means. Radars are instrumented in a number of ways. Three common methods and their associated shortcomings are: • **Switch Position** – the instrumentation records the time when the switch is engaged. Instrumenting the switch position tells the analyst when the operator commanded the transmitter to turn on, it does not represent the time that the transmitter actually began radiating. This is a potential error source, since there will be a time difference between the time that the switch was engaged and the time that the transmitter began radiating. This time difference will vary by system and can even vary within a system, for example, a transmitter that is warmed up may come up to full power more quickly than a cold one.	It is critical that data analysts understand what is being measured, how the MOPs are specifically defined, how accurately the data will allow the MOPs to be calculated, and how these relate to the specified system requirements.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Understand timing relationships, measurements, and uncertainty (cont'd)	• **Data Bus Message** – modern radars and simulators employ software controlled elements and can record when the message commanding the transmitter to engage was sent on the data bus. In this case the initial time will be after the operator commanded the transmitter to turn on. There will be a lag until the command is sent on the data bus. As is the case of instrumenting the switch position, the instrumentation system only records the time that the transmitter was commanded to radiate. • **Radio Frequency Transmitted Signal Power Level** – a RF detector measures the signal output power level at the transmit antenna. When the signal level exceeds a predetermined threshold the instrumentation records the time of the event. This method can at times actually induce an unusual anomaly: a negative response time, i.e., the SUT receiver detects the RF signal before the instrumentation system records that the radar is transmitting. This can occur because the transmitted power ramps up in amplitude and takes additional time to exceed the reporting threshold. This is most likely to occur when SUT receiver is fast and very sensitive and the radar has a relatively long ramp up time. Each of these methods can introduce errors and measurement uncertainty.	
Record SUT details and test configuration	Record serial equipment being tested along with the time and date of test. It is amazing how quickly measurement data becomes worthless when a question arises later and the exact test configuration cannot be ascertained or recreated. Although simple, obvious and begging the question "Why is this even in a lessons learned list?", international experience has shown this to be an intermittently recurrent and fully preventable problem for over 30 years.	• All test engineers need to be very disciplined in this regard and treat their test configuration like that for an academic research trial. • All necessary data must be recorded to enable a third party, at some later date, to exactly replicate the test and its results.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Monitor the power line during tests	Fluctuations on the power line due to other laboratory equipment being turned on or off may affect the performance of the system being tested. If the surges are outside the permitted limits of MIL-STD-704 or the particular SUT specification, full SUT performance is probably not required and it shouldn't be classified as a test failure. The same is true when ground tests are performed on an aircraft using an auxiliary power unit versus running the aircraft engines. If the power isn't automatically monitored using external equipment, the wrong conclusions about the system's performance may result. Also, ensure that monitoring equipment works. A disturbance analyser was flown in a military aircraft to try to determine why the on-board jammer and RWR were occasionally resetting. After 20 minutes, extensive transients were recorded on phase C of the aircraft power. Since some of the transients seemed too high, the disturbance analyser was tested on the ground. After letting it run for 20 minutes with nothing connected to the input, it started dispensing a tape documenting all kinds of erroneous "transients" on phase C. The disturbance analyser had an overheating problem and we were back to square one on identifying the aircraft problem.	• Monitor power lines in the laboratory and during aircraft trials, as voltage interrupts and transients, and spurious and harmonic signals have been the root cause of a number of problems with EW and other avionic equipments. • Be ever mindful that test equipment can be as problematic as the SUT under test. Never discount T&E equipment, especially if containing software, as a SUT problem contributor until you are doubly sure this is true.
Effects of component response time	A number of problems have been experienced whose root cause was the apparently innocuous change of an internal component's response time. Three examples are provided: • A component manufacturer made an assembly change that resulted in an Integrated Circuit (IC) having a faster response time. The static discharge that occurs during airborne refuelling was now sensed by the IC and caused system susceptibility. Therefore, units with the same part number worked differently due to a subtle change in a replacement component. • A comparison path in the receiver of a jammer would occasionally have inconsistent results. The problem was traced to a manufacturing change made by a supplier on an IC that resulted in a faster response time. Therefore, signals from one path were arriving at the comparison circuit too soon to be compared with signals from another path. • An aircraft's new blanker box worked less well than its predecessor. The newer components operated significantly quicker than the older components. The original blanker box specification only stipulated the maximum delay through the circuitry; there was no minimum delay requirement because the "state of the art" at the time of the original design would not allow a problem to occur.	Always suspect a changed component if timing problems appear on an upgraded SUT and platform installation that previously worked correctly with the earlier version of SUT.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Determination of test point limits	As part of acceptance testing a HPM signal was applied to a system and no damage occurred. When a low power signal was input into the system, normal system operation was observed. However, during middle-level power testing the system suffered damage. The reason was that a Sub-Miniature A (SMA) elbow connector between the system's antenna and receiver caused the HPM signal to arc. This arcing dissipated the high amplitude energy before it reached the receiver. A middle power level did not arc across the SMA elbow connector, but the power was high enough to burn out electronic components in the receiver. In another instance, the ability of the automatic recovery circuitry of a system to respond to the loss of power for short intervals was tested for losses of aircraft power for a duration of one microsecond and 1 and 10 ms. The system continued to operate properly through the short microsecond dropout of power. Its operation ceased during the 10 ms dropout of power but it automatically recovered when power was reapplied. The system never recovered after a 1 ms dropout of power. The reason was that the system logic was programmed to handle one thing at a time and it was still sequencing through its powering down routine when it received a signal to power up; the logic was not in place to accept this command so the system just hung up. During the 10 ms power drop out test, the system had already completed its power down cycle when the command was received to power up, so it properly followed the command.	• Test points should be selected carefully and, where possible, should be chosen to probe the correct operation of a particular element of function or performance. • Avoid selecting 'maximum and minimum only', as experience shows this often hides problems that emerge later.
Radomes – characterisation and post-repair testing	Radomes are used on aircraft nose radars, jammers, RWR/ESM antennas and other RF transmitting/receiving antennnas. Various problems affect their use and effectiveness, most of which impact all types of radomes, and some – such as described below – are particular to nose radar radomes. A nose radar radome serves several purposes. First, it provides an aerodynamically correct shape to the aircraft nose. Second, it shields the internal radar and other avionics from the effects of weather such as rain, sand, etc. It must perform these tasks and remain electrically transparent to radar energy, whilst transmitting and while receiving. The measure of this 'transparency' is known as transmission efficiency. The radome must be designed for the particular radar frequency by matching the cross-section structure, thickness, dielectric constant, and materials. Final testing is performed in an anechoic chamber with and without the radome. If a radome is poorly designed or is	• Radomes should be fully characterised after damage repair. • When newer radars are fitted into older aircraft, the radomes need to be checked to ensure proper transmission of the new RF energy and the new radiation pattern.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Radomes – characterisation and post-repair testing (cont'd)	damaged, and then is repaired without using proper procedures or testing, the transmission efficiency may be impaired. Figure 9-1 shows the transmission of a radome which had been improperly repaired in the nose area. The "curve" should normally be flat.  **Figure 9-1: Transmission Efficiency.** As can be seen, the area directly ahead has a worse transmission efficiency. This can have a major operational impact because an aircraft could be flown into a bad storm, thinking that better weather (weaker return) was in the direction straight ahead. It is postulated that this is what caused at least one aircraft accident several years ago. In addition to not 'seeing' weather or targets in selected directions, an improperly designed or repaired radome can create false targets as shown in Figure 9-2. In this particular case, ground return may depict a false 'storm' ahead which is at a distance that the aircraft is above ground level.	

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Radomes – characterisation and post-repair testing (cont'd)	 Figure 9-2: Radome Ground Return. Note: Figures and background material contributed by Ben MacKenzie, Director, Technology and Engineering, Norton Performance Plastics Corp., Ravenna, Ohio.	
Look at data cross-over regions	During testing, data are frequently taken with several test setups (or layouts) in order to accommodate different measurement scales or instruments covering a different frequency range (or some other variable parameter). It is wise to ensure that data points overlap the ranges of data measurements and that the results in this cross-over region are similar, if not identical. In cases where different bandwidths are used in the amplitude measurement of pulsed signals, there may be a loss in amplitude since one bandwidth may be narrower, but the difference should be explainable. If there is an unexplained difference in the cross-over region, the spectrum analyser may be saturated by a strong out-of-band signal. If an external 10 dB attenuator is inserted, all data should drop by 10 dB. If not, an RF filter needs to be added to reject the interfering out-of-band signal to get valid measurements.	Sub-banding of tests, for a variety of reasons, is commonly required to fully cover a particular SUT performance measure. In this case ensure that data is measured to enable verification that data elements in adjacent sub-bands are identical (within measurement error) or fully and satisfactorily explainable.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Don't make assumptions when reporting problems	The system/avionic problem report is the primary method of getting SUT problems fixed. To aid speedy resolution without the need for subsequent investigations, it is important that the test engineer provide as comprehensive and complete a record of the problem, with supporting evidence, as is possible. The report should also be accurate – two examples follow where an incorrectly made assumption hindered rather than helped resolution of the problem: • When a RFCM system was initially deployed on an aircraft, it was reported to have transmitted on the carrier deck while in the receive mode. What actually occurred was the transmit light illuminated when the RFCM system was in the receive mode. The witness assumed that since the transmit light was on, the RFCCM system was transmitting. The RFCM system was found to have circuitry for the transmit light that would inadvertently illuminate in either the presence of certain high power RF or certain types of vibration. • In another case, test personnel reported a jammer continued to transmit long after the input signal was withdrawn. What actually occurred was the system would go into a ring-around condition after the signal was withdrawn, and instead of transmitting a high level signal, only low level noise was transmitted. The transmit light illuminated the same but the output power was significantly different. Finding the solution to the problem was delayed due to assuming the transmission was the same because the light didn't change intensity.	• Ensure system/avionic problem reports are accurate, precise, comprehensive and complete. In general, the better the problem report, the quicker the solution. • Provision of photos, figures and other evidence that might help the equipment/ software supplier to pinpoint the problem's root cause is strongly recommended. • Don't make assumptions – double check the facts.
On-aircraft RF coupling (interference) may not be symmetrical	Symmetry of RF coupling, based on a simple view of transmit and receive antennas' placement on an aircraft, is often and reasonably used to justify clearance of a full performance envelope based on extrapolation of a sub-set of physical measurements on that aircraft. For example if RWR antennas are identically mounted at the top extremities of both wings, then coupling from an in-band RF transmitting antenna on the top centre of the fuselage to any of the RWR antennas will be very similar, if not identical. There are cases, unfortunately, where this RF coupling is asymmetric to a greater or lesser degree. For example RF coupling, which may cause interference, from the radar in the nose of the aircraft to symmetrically located EW (or other) antennas on each wing, may not be identical. If the radome for the radar is hinged on one side, the radome material will be thicker on that side and will cause more	• Symmetry of on-aircraft RF coupling paths should not be assumed, especially when attempting to justify a reduced T&E programme based on that symmetry. • Antenna pattern modelling should be used to predict the level of symmetry likely to occur on a given platform, which should then be validated by a limited set of measurements.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
On-aircraft RF coupling (interference) may not be symmetrical (cont'd)	attenuation to the backlobe of the radar signal that could couple to other aircraft antennas. If measurements are only performed on that side, no interference or reduced interference could be measured whereas the "mirror image" antenna on the other wing could be receiving more signal and therefore more interference.	
EW man-machine interface	Sub-optimal MMI is a common theme running through many of the problems previously seen during EW T&E. In some cases there has been scathing criticism by aircrew and engineer alike concerning EW display presentation, usefulness and confusion caused when trying to use it 'in anger'. The execution of MMI assessments early in the design life-cycle, as is more often the case nowadays, helps prevent this type of problem reaching the aircraft, where it is more costly and time-consuming to fix.	Engage EW T&E engineers and aircrew in MMI assessments during the design phase, to minimise problems at the rig and aircraft test phase.
How to know if the problem is the avionics system or the platform	When a SUT passes Intermediate-level (I-level) tests, then fails in an aircraft, and fails a repeat I-level test, suspect aircraft wiring if this sequence occurred in the same aircraft. For example, on one aircraft carrier, seven jammers were tried in an aircraft and none of them passed self-test. All failed subsequent I-level tests. Finally, aircraft wiring was checked and a short was found which was damaging the jammer interface circuitry. When a system passes I-level tests, and fails in an aircraft, then re-passes I-level tests, suspect aircraft wiring, physical or environmental considerations: • In one case, a keying connector wasn't connected and the extra sensitivity that was supposed to be activated in this installation wasn't obtained. Consequently the jammer failed flight tests against a certain radar. • In another case, the system power supply coolant was low; so when the jammer was flown, the sloshing, shifting coolant uncovered high voltage electronic components that arced thereby causing a failure. In the I-level test facility, the jammer was always tested in a level position and no failure occurred. As a result, test preparation instructions were changed to include testing with one end slightly elevated if a sloshing fluid noise is heard during handling.	• If a serviceable EW SUT is fitted to an aircraft for the first time and it fails, immediately suspect and investigate the aircraft wiring. • Unless unavoidable, **do not** fit a replacement SUT until the faulty original unit has been investigated and the aircraft and its wiring cleared of involvement in causing the fault. • If a serviceable SUT is off-aircraft re-confirmed as still being serviceable after failing on the aircraft, initially suspect broken wires or incorrect, faulty or mis-connected connectors.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Try to arrange measurements so measurement errors are obvious	The test engineer can help him/herself by designing tests that include an element of 'self-checking'. Two examples are given here: • When multiple frequency measurements were made of a jammer's frequency spectrum, three measurements were necessary, i.e., in-band, out-of-band at higher frequencies, and out-of-band at lower frequencies. To preclude saturation of the spectrum analyser when lower power measurements were made at the lower frequencies, it was necessary to use a Low Pass Filter (LPF) to attenuate the strong in-band signal. To preclude measurement data being used when the filter was inadvertently not inserted, the frequency measurement range was extended high enough to include part of the roll-off portion where the LPF was starting to filter. Therefore, all valid measurements showed a decreasing slope in the jammer's thermal noise at the upper limit of the measurement range. • When antenna-to-antenna isolation tests were performed on jammer antennas on an aircraft, the engineer always performed the test twice. The first test had the energy sent directly into the spectrum analyser. During the second test an external 10 dB attenuator was attached to the analyser. Therefore, if the analyser's noise floor was being measured in the first set of data (without an attenuator), there wouldn't be a 10 dB difference with the second set (with the attenuator), i.e., data were invalid and the isolation was greater than measured.	Where possible, design tests that enable the test engineer to quickly identify if measurement errors are present.
SUT instrumentation and data recording	Even if you have done a very good job under the T&E period with a lot of defined test cards, there will always be situations during flight test operations that the SUT does not behave in a correct way and which was not defined in test cards and perhaps situations that are difficult to recreate. To make it possible to analyse that type of problem it is necessary to have a recording system running all the time.	It is very important to have a very "powerful" internal recording system dedicated for EW purposes in every military aircraft, especially those going in harm's way.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Airframers need to know what the avionics contractor is thinking	The following examples, although really design and ICD issues, are typical of the more subtle installation problems that can get through to aircraft to be found by the astute test engineer: • In one case, the jammer manufacturer assumed that the system's cooling exhaust fans would not be engaged in a ram air-cooled aircraft because a fan disable switch would be depressed when the cooling plenum was attached to the front of the jammer. The airframe manufacturer didn't know that and designed the cooling plenum with a cut-out to leave the switch alone. The jammer contractor didn't realise it until one technical representative reported hearing the fans running while the aircraft was on the ground. • In another case, an older jammer relied on the external coupling of the jammer output to the receiver to completely fill the internal loop delay line with RF energy. The jammer installation only specified the minimum external ring-around attenuation and delay but not the maximum values; therefore, some airframers thought that more attenuation/delay was better and none of the transmitted signal filled up the delay line. As a result, the transmitted signals had gaps between each recirculated segment used to build up the transmitted pulse. It should be noted that in this case, even if the optimum attenuation and delay had been obtained, the combining of out-of-phase pulses/pulse segments caused spreading. Nevertheless, the airframer needs the complete information from the system designer when the characteristics of the aircraft installation affect the system design.	• Before testing on SIL/HITL rigs and on aircraft, engineers should become familiar with the SUT specification and relevant ICDs. • Attention should be paid to the operation of on-aircraft, free-space RF feedback loops as used on many RWR/ESM/ECM systems. These should be replicated or simulation on SIL/HITL rigs. • These rigs should include the same number and type of interlocks and switches as are installed on the aircraft. Test procedures should correctly cover their operation. • Particular attention should be paid to the function and operation of 'Weight-on-Wheels' ('Aircraft-on-Ground') switches, problems with which has been at the root of many past EW SUT and T&E problems.
Multiple reporting of EW/Avionic problems	An investigation of DAS T&E rig and aircraft ground/flight trials during a many-year development programme on each of two platform types showed that – with the benefit of hindsight – many more system/avionic problem reports had been raised than was necessary. This resulted in the two programmes being longer and more costly than they could have been. This experience is known anecdotally to be generic across the EW T&E community, although process and procedure enhancements in recent years have improved the situation. The reason for duplicated problem reports fell into three categories, those:	To minimise the risk and number of repeat or duplicate problem reports on a programme: • Always adopt an Integrated Test and Evaluation Approach. • Where the same or similar variant of EW equipment is fitted on one or more platforms/variants and is to be fitted to another, always screen open and closed

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Multiple reporting of EW/Avionic problems (cont'd)	• Initially raised on SIL/HITL facilities that were re-investigated and re-raised on aircraft ground and/or flight trials. Sometimes the exact same problem is raised at the rig, aircraft ground test and flight test, with the latter two duplicate reports adding nothing to the original one. • Raised on EW equipment on one platform type then re-raised on the same or very similar equipment fitted on another platform type at a later date. • Which are different facets of the same problem. • The single root cause identified is inadequate visibility to ALL involved departments/agencies of the existence and latest status of problem reports.	problem reports that were raised on the earlier platform/variant.
Use and limitation of video recording during aircraft RF EW trials	Much EW T&E work in the last two decades has been in the area of relatively high power on-board transmitters interfering with sensitive on-board receivers. Measurement of interference has often been subjective, i.e., by aircrew/engineer comment on displays and/or post-trial analysis of video recordings of EW and other RF equipment displays. Whilst video recording is a powerful development tool and has been used on SILs for many years with great success, it has had a number of shortcomings when considered in the on-aircraft EW context. These are: • Subjective and qualitative, rather than quantitative measurement of results of jamming and/or RF interference. • Often poor quality video, caused by the use of cockpit mounted TV camera(s) rather than direct recording of display surface video signals. • Substantial time and effort overhead in post-trial analysis, including the necessity to use experienced EW engineering effort.	Use direct video recording of display surfaces for T&E investigations of jamming and other interference on on-board EW and other radar frequency receivers.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Conformance to Specification vs. 'Fit for Purpose'	The primary emphasis of Industry T&E engineers in earlier times was to confirm that the platform and EW SUTs met the functional and performance requirements defined in their contract specifications – the basis of being paid by their defence ministry and armed forces customers. This led to some problems encountered on rig and aircraft trials being declared as 'Meets the specification, this is not a problem.' There is now a wider recognition that *Fit For Purpose* does not mean, as was historically the case, *Meets the specification*. The combination of specifications, ICDs, and an associated '*Capability and Limitations*' document provides a clear view of what is and, as important, what is not being provided under a contract. This enables proactive and early resolution of any items that might not be acceptable to the customer. Customer and military end-user agreement to this latter document provides a consistent, all-stakeholder definition of *Fit For Purpose*. In addition there is an implicit understanding that the SUT needs to be free of serious 'bugs' at the point of delivery to service and during its operational life. This adds a dimension to the above – to approximately quote an American systems engineer "Proving conformance to specification does not prove the absence of faults". It has been observed over many years that a substantial element of the overall T&E effort on EW and other avionic systems has been spent on finding and fixing software/hardware bugs rather than on merely demonstrating conformance to specification.	• Produce at contract outset a Capability and Limitations document for a given EW SUT or DAS, agreed by all stakeholders. Update as appropriate during the contract. • Use this document in conjunction with SUT specifications and ICDs to guide and optimise the scope, duration and cost of the EW T&E Plan.
Tape recordings can help pinpoint audio interference	When audio interference was heard on an aircraft internal communication set, a tape recorder with high frequency metallic tape capability was used to record the sounds with the interfering system on and with it off. The recording was then played back into a spectrum analyser with the 'max hold' function selected. By comparing the two spectrum analyser presentations, the frequency of the interference was calculated, which then enabled engineers to determine the specific circuits causing the interference.	As with video recordings, see other lessons learned, high quality audio recordings can be very useful when investigating on-aircraft interference.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Unexplained EW SUT effects during testing	During rig and aircraft ground and flight trials sensitive EW receivers have, on a number of occasions, suffered from display freezes, software re-starts and stoppages, and/or inaccurate/ambiguous fault indications. Many have, upon investigation been either 'unexplained', 'unrepeatable', 'not understood' or considered (usually by the equipment supplier) as 'unrepresentative test'. Some have been traced to sensitivity to supply voltage transients when other, high current aircraft equipments are turned on or between off, standby and on modes, i.e., an EMC/EMI problem. Others are thought to fall into a category of 'catching' the EW computing hardware/software at some time-critical point in its processing cycle. This type of problem is generic to computer systems and can be extremely difficult to repeat, fully diagnose and solve. Despite this, it is thought from the circumstantial evidence gathered over the years that many may, in the final analysis, have been caused by noise/voltage transients on signal or earth lines either within the EW system or at the interface with the aircraft supplies.	To aid replication, investigation and resolution of any such problems: • Use video recording during tests. • Monitor power lines into and out of the EW receiver system's own power supply unit.
'Subjective' investigation of RF coupling problems	Much EW T&E work in the last two decades has been in the area of relatively high power on-board transmitters interfering with sensitive on-board receivers. Investigations of such problems, especially when involving ECM systems, have been lengthy, some have been inconclusive, and a number have been very cost-ineffective – resulting in little or no improvement. This resulted from one of more of these reasons: • No modelling of ECM to RF antenna/receiver coupling, which would immediately identify the type of interference (in-band transmitters affecting in-band receivers, or out-of-band interference). • No in-depth assessment of the problem and its causes, or review of equipment design to establish if potential solutions were capable of offering required level of improvement. • A minimum of antenna coupling measurements, necessary to confirm those predictions. • Subjective assessment of interference seen ("better than before" – even if it is still considered unacceptable). • Limited quantitative measurements of victim SUT-received interference power/frequency.	To minimise technical risk and RF interoperability test timescales: • Prior to aircraft tests use M&S (Computational EM) to establish whether there is likely to be any inter-system interference. • Confirm correct RF interoperability via whole aircraft tests in an anechoic chamber ISTF. • Conduct a minimum of on-aircraft investigations when/if unexpected interference is encountered. Then go back to the M&S models to investigate the problem and potential solutions prior to returning to the aircraft for further testing.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
'Subjective' investigation of RF coupling problems (cont'd)	• Somewhat un-scientific approach to possible solutions: stick a bit of RAM here, then there; swap ECM from one wing to the other; RAM paint application.	
The utility of 'Confirmatory' testing	Prior investigations have shown that in most cases each successive stage of tests, (Supplier CoC, Platform Supplier Acceptance Test, SIL Pre-Integration/Integration, aircraft ground test and flight test), is broadly a sub-set of the earlier one, but with much repeat test work being conducted. If this situation is inspected logically from a cost effectiveness point of view, no test should be repeated unless it either demonstrates an aspect of conformance to specification or is specifically requested by the Customer in the contract. This request, if it is present at all, is likely to be more of a Public Relations exercise – giving him 'confidence' – rather than a technical necessity.	• Screen existing test plans and procedures to remove redundant and costly "confirmatory" tests. Avoid their use in future plans and procedures. • In this way the SUT supplier's tests should be the most technically exhaustive followed, in decreasing order of duration and complexity by avionic rig, aircraft ground and aircraft flight testing.
Problems with RF connectors	Two primary problems have been experienced repeatedly over the years and across a wide variety of platforms: • Aircraft RF cables, when connected to EW equipments, have not always been torqued up correctly. In some cases they have only been connected 'finger tight'. For correct EW SUT performance it is essential that all RF connectors are correctly torqued up. Failure to do so can lead to degraded performance – sometimes not bad enough for the SUT's BIT system to detect but bad enough to adversely affect overall threat direction finding, detection and identification performance. Sometimes the BIT will indicate a faulty LRU when, if fact, there is no problem with the LRU. This can lead to lost test time, nugatory investigation and the availability impact of LRU 'No Fault Found'.	• When connecting aircraft RF cables to EW black boxes always correctly torque up RF connectors to assure performance and prevent problems. • Double check RF cable connections to EW RF receiver LRUs/LRIs on SIL/HITL avionic rigs and aircraft. • Check for the RF cable swapping problem on RWR/ESM installations by conducting a simple, walk-around quadrant check using a RF signal source.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Problems with RF connectors (cont'd)	• Aircraft RF cables to RWR/ESM antennas and/or receivers being accidentally swapped over due to lack of connector keying or difficulty seeing connector idents on the LRU when installed in the aircraft. An often result of this is that emitters in two quadrants appear in the opposite quadrants. This kind of mis-connection can be trapped by a walk-round test of the aircraft using a hand-held RF emitter simulator.	
Use of SIL and HITL facilities for EMC testing and investigations	Generally, the aircraft is the only real place where full system EMC can be confirmed. The risk of EMI and other EMC-related problems is minimised by robust design practice and EMC qualification of individual LRUs/LRIs. Historically, avionics rigs with SIL and HITL facilities were not designed or suitable for EMC testing. Nowadays many modern avionic rigs use aircraft grade cable with representative lengths, they utilise aircraft screening/earthing/bonding schemes, and have 'cockpits' with aircraft equipment laid out as they are in the aircraft. Whilst predominantly designed this way from an integrated avionic system testing standpoint, this has made them more electromagnetically representative of the aircraft. Some limited, system-level EMC risk reduction work can be conducted on the SUT on such rigs. Pulsed and CW RF Bulk Current Injection tests have been shown to have good correlation with on-aircraft test results. This can aid early identification of problems, prior to aircraft use, and provides an off-aircraft investigative tool for EW and other avionic EMC/EMI problems.	Consider the use of avionic rigs in SIL/HITL facilities for EMC/EMI testing and investigations.
'Parallel' SIL and aircraft flight testing	A few examples of 'parallel' testing have been seen. This is where a software and/or hardware update or new package is delivered to the SIL and aircraft at the same time. A bare minimum switch-on clearance test is conducted then the aircraft ground/flight trials are allowed to proceed in parallel with full SIL integration/assessment activities. Whilst this approach can theoretically be used in an attempt to save time or recover development programmes experience shows this to be a high risk, poor payback option in practice. All that happens is the problems, some of which are major, which should have been found on the rig, are instead first found in flight with a much higher cost and timescale penalty. In one case a two-aircraft flight trial and associated post-trial investigations were totally wasted.	• Ensure optimal use of SIL (sub-systems and avionics integration) facilities by following the Integrated Test and Evaluation and Acceptance process. • Do not take the risk of jumping straight to flight test without passing EW and other avionics through the SIL process.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
'Un-repeatable' test problems	There are occasions where a problem has been seen once during EW rig and aircraft trials with the SUT and/or with test equipment being used in the T&E process, but which cannot at that time be repeated. In the past some have either: • Chosen to ignore the occurrence ("It's not repeatable, so cannot be a problem."); • Attempted to repeat the problem a small number of times as part of the ongoing trial, after which it is declared not to be a problem; or • Decided not to record/progress any definitive action to reproduce it beyond that briefly conducted during the ongoing trial. Some such problems have only re-surfaced again once the platform has been in operational use for some time. Some of these have had unacceptably adverse operational impact and a significant amount of time and effort has then had to be expended 'hunting gremlins' – usually with some success. Some problems have been repeatable and on more than one occasion the problem has been repeated, but only when an out of the ordinary (but allowable) sequence of keyboard or other 'button' pushes has been effected. A phrase often encountered over the years when sharing experiences on such problems with other users of the SUT and/or platform and/or test facility/equipment is "We've seen that!" – accompanied with the information that they also haven't formally recorded the problem either, for the same reasons as above.	• Record all problems seen during trials using the system/avionic problem reporting process, then move any un-repeatable problem to a 'Watch List' if not re-encountered within a reasonable period of time. • Ensure all relevant stakeholders in the platform and SUT (as appropriate) are aware that there is a risk of such problems recurring at some point during the SUT's operational life. • Optimise problem early fix potential by sharing such information with the manufacturer of the test equipment, SUT or platform.
Investigate test response when SUT is not connected	A test result may not be what you expect when a system is not connected. For example, while evaluating the effectiveness of I-level tests of a jammer on a piece of Ground Support Equipment (GSE), the tests were run on the GSE without the jammer connected. Surprisingly, five of the 100+ tests passed! It turned out that the noise floor of the measurement instruments in the GSE was being measured and its power level was within the limits of these tests for the jammer. Therefore, these particular tests could never fail and they needed to be changed.	• Be mindful that test equipment is not perfect. This includes GSE, COTS (e.g., spectrum analysers) and other Special-To-Type Equipment. • Some can, under certain conditions, provide indications or give measurements that incorrectly suggest a 'Pass'. • Familiarity with the test equipment is the best defence against this type of problem.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Commonality of test tools and training	• Cases have been encountered where different sites/divisions of the same company have obtained different results from testing due to the use of different measurement equipment and/or procedures and/or training. • This is especially relevant when considering RF EW tests conducted at different sites, divisions, agencies and companies, where different RF threat simulators and other emitter generation equipment has been used.	• At the T&E planning stage, ensure appropriate levels of test tools and training commonality across the test engineering stakeholders irrespective of their agency. • If adequate commonality cannot be determined at that point, factor in how the differences will be taken into account during the T&E process.
Microwave testing problems	A number of typical problems have been encountered during microwave testing at various levels, from EW component, box and system testing in the laboratory, via SIL/HITL to aircraft testing in ISTF and in support of flight test and trials. Learning points for a few are presented at right.	• Always use isolators in any microwave test set-up, to minimise risk of damage to un-protected components. • Always take a transmission and reception measurement before starting to test: this will provide the tester with the current equipment set-up losses which can be taken into account. • Ensure that component, sub-system and system tolerance coning is correctly carried out prior to commencement of practical T&E. • Always check that the antenna under test is on boresight before commencing initial radiation pattern measurements. The non-use of a simple VSWR meter to obtain this is common practice and lends itself to poor results being gained.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Microwave testing problems (cont'd)		• Check that antenna radiation patterns do not show signs of bifurcation on the main lobe: there are times when such a feature is so small that it is easily overlooked. It is at this point that judgement needs to be made as to whether reposition, or continue testing.
Basic test set-up	The use of basic test set-ups is good practice. Too often have engineers used previous test set-ups only to find at a crucial point that their results are invalid because a small but important item of test equipment was missing.	• Have a basic test configuration thought out and always return the equipment to this state following the completion of a phase of testing. • Have basic test set-ups detailed in block diagram format and available to non-RF engineers. This enables seconded personnel to set-up equipment by themselves. It was then checked by engineers familiar with RF before test commencement.
Test equipment calibration	Test equipment being found out of calibration at the start or during a test phase remains a problem that is intermittently encountered. Another facet is when an item goes out of calibration just after the originally planned test completion date – but is now a problem as the aircraft trial has been extended.	• Ensure all required test equipment for a given test phase will be inside calibration for the duration of the trial. • Ensure sufficient schedule reserve on the calibration past the planned completion of the test phase. If this is not possible, arrange loan or hire of a replacement equipment to minimise risk to the test programme.

TOPIC AREA	PROBLEM, ROOT CAUSE AND COMMENT	LEARNING POINT
Adequacy of 'problem' and 'equipment failure' time	Invariably test and/or SUT failures are encountered during T&E programmes. Problems are also usually encountered during the testing, which require investigation – some at the time and more at a later point during or at the end of the tests. Often the planned programme schedule does not allow sufficient time to cater adequately for these realities of T&E.	• Plan testing thoroughly: build in problem investigation time and equipment failure time. • Plan which test elements have priority 1, 2 and 3, should such problems and failures occur during a given test phase. Agree this with the customer before beginning. Have a mid-test meeting to discuss progress and problems. Hold an end-of-test wash-up meeting.
Airframe harmonic effects	The energy radiated by higher order harmonics of a high power transmitter on an aircraft interfered with the operation of other onboard systems. To solve the problem two changes were made. A low-pass filter was incorporated into the system output design and the system's antenna was designed to minimise the generation of second, third, etc., harmonics. Anechoic chamber tests indicated the design objectives were met, but when the system was installed on the airframe, interference was still seen on other onboard systems. The problem was determined to be that the dissimilar metal surfaces of the airframe acted as non-linear devices and induced harmonics onto the reflected signal. In an initial attempt to change the characteristics of the reflections, the wing surface was pounded with a rubber mallet! The harmonics disappeared but shortly thereafter they reappeared.	• Transmit and receive antenna function and placement is best optimised using Computational Electromagnetic Modelling (CEM). • This includes maximising isolation between in-band and harmonically related antenna pairs, and maximising coverage (polar patterns) in required directions. • CEM is beneficial when introducing or re-locating antennas. • CEM's benefit is multiplied when dealing with antennas on airframes made of dissimilar materials, e.g., Carbon Fibre Composites, titanium and aluminium.

9.4 REFERENCES

[1] Berkowitz, P.H., "EW Testing Lessons Learned", Track: SOS/DST 16 June 1998. Report: A302553. Internet: http://dodreports.com/pdf/ada355203.pdf. Last accessed: 12 October 2011.

[2] Stadler, K.M., "Test and Evaluation Lessons Learned from the Field", Defense Acquisition Journal, September 2007, pp. 396-408. Internet: http://www.dau.mil/pubscats/PubsCats/ARJ45_Stadler.pdf. Last accessed 12 October 2011.

9.5 FURTHER READING

Conference Proceedings for the annual U.S.A.F. T&E Days, organised by the American Institute of Aeronautics and Astronautics. Internet: http://www.aiaa.org/content.cfm?pageid=320 Last accessed 25 November 2011.

Annex A – ELECTRONIC WARFARE T&E FACILITY DESCRIPTIONS

A.1 INTRODUCTION

This annex provides descriptions of known EW and related T&E facilities in NATO Nations. Whilst it does not fully describe every resource that a project may wish to utilise, it represents a valuable resource for understanding the range of facilities available to meet the goals of a structured test process.

A.2 FACILITIES LISTING

This annex was compiled by the authors with the help of the national representatives on SCI FT3, and it is the most current available at the point of issue. All information has been provided by the respective facilities. It is non-exhaustive; for new and/or upgraded facilities information, check with your national representative. To assure the latest information on any facility or resource, engage with the Point of Contact given at the end of each listing.

NATION	FACILITY/RESOURCE NAME	ORGANISATION/LOCATION	PRIMARY DESIGNATION
GBR	Electromagnetic Modelling Group	BAE Systems, Lancashire	M&S
ITA	Antenna Design and Testing Group	Alenia Aeronautica S.p.A., Turin	M&S
DEU	Cassidian Computational Electromagnetics	Cassidian, Manching	M&S
USA	Integration Facility for Avionic Systems Testing	USAF, Edwards AFB, California	SIL
USA	Portable Seeker/Sensor/Signature Evaluation Facility	USAF, Eglin AFB, Florida	SIL
USA	ECSEL	USN, Point Mugu, California	HITL
USA	Benefield Anechoic Facility (BAF)	USAF, Edwards AFB, California	ISTF
GBR	EW Test Facility (EWTF)	BAE Systems, Lancashire	ISTF
USA	Air Combat T&E Facility (ACETEF)	USN, Patuxent River, Maryland	ISTF
GBR	Electromagnetic Test Capability	BAE Systems, Lancashire	ISTF
ITA	Anechoic Shielded Chamber	Alenia Aeronautica S.p.A., Turin	ISTF
ITA	Electromagnetic Open Area Test Sites	Alenia Aeronautica S.p.A., Turin	ISTF
USA	J-PRIMES	USAF, Eglin AFB, Florida	ISTF
DEU	Cassidian EME Test Facility	Cassidian, Manching	ISTF
USA	Electronic Combat Range (ECR)	USN, China Lake South Range, California	OAR
SWE	Vidsel EW Test Range	Swedish Defence Materiel Administration, Vidsel	OAR
USA	Center for Countermeasures (CCM)	US DoD, White Sands Missile Range, New Mexico	OAR
GBR	Joint EW Core Staff	NATO, RNAS Yeovilton	OAR
USA	T&E Support for Aircraft Survivability	USAF, Eglin AFB, Florida	OAR
GBR	Trials/Test Support Group	ESL Defence Systems, Hampshire	OAR

In addition to the above, some Nations also maintain a catalogue of T&E capabilities, some of which are applicable to EW. Examples include:

NATION	CATALOGUE TITLE/REFERENCE	CONTACT
GBR	UK Test and Evaluation Catalogue D/Wpns/TEST/03/02/07/CatalogueV6 dated July 2011	DESWpnsTEST-TECC2@mod.uk

A.3 MODELLING AND SIMULATION RESOURCES

A.3.1 Electromagnetic Modelling Group

TEST RESOURCE CATEGORY

Primary: M&S / Other: (Not Applicable).

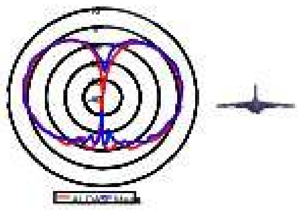
LOCATION

BAE Systems, Military Air Solutions, Warton, Lancashire, UK.

NARRATIVE DESCRIPTION

The Group has access to a suite of Computational Electromagnetic Modelling (CEM) codes covering all the major frequency and time domain modelling techniques (see Capability Summary). These are used on a 512 core parallel processing supercomputer capable of 1.5 TFLOPS with 1.5 TBytes of core memory, which is dedicated to electromagnetic modelling.

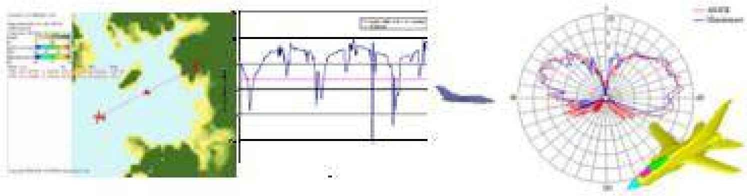
The Group can import design data (structure, cabling and pipework, including material properties), directly from Computer-Aided Design (CAD) systems and, with a minimum of intervention, automatically create suitably gridded geometries. Thus 1 billion cell models are regularly created and analysed. For microwave frequencies the ray tracing codes are available.



This computational facility is utilised by the Group's experienced, specialist engineers to provide solutions to a wide range of electromagnetic problems including installed antenna performance, in terms of polar diagrams, antenna coupling and RF systems performance. The latter uses the installed antenna modelling output in modelling tools which enable assessment of communications link performance in different scenarios and platform, RF interoperability analysis.

The capability is also used to simulate the interaction of lightning, Electro-Static Discharge (ESD), Electromagnetic Pulse (EMP) and High Intensity Radiated Fields (HIRF) with systems internal and external to any platform, including cable currents and equipment electromagnetic environment.

It is used throughout the design and support life-cycle to establish concepts, carry out design optimisation and risk reduction through to design verification and supporting qualification of 'first of type' and upgrades during in-service support.



CAPABILITY SUMMARY

Electromagnetic Software Tools

Most of the applications software has been developed and maintained within BAE Systems to meet general requirements across a broad range of products and design solutions. A key aspect of these facilities is the link to CAD generated geometry accommodating all major CAD systems.

All major electromagnetic modelling codes/methods are represented including:

- Transmission Line Method (TLM)
- Finite Difference Time Domain (FDTD)
- Boundary Element (BE)
- General and Uniform Theory of Diffraction (GTD/UTD)
- Fast Multi-Pole Method (FMM)
- Hybrid finite element / finite difference
- Antenna communications link modelling software
- Antenna coverage modelling software

Applications

The engineers are experienced in applying our modelling tools to address a wide range of electromagnetic threats, interactions and issues seen on vehicles, systems and other structures including:

- Installed antenna interoperability (coupling)
- RF systems performance, including the propagation path
- Un-installed and installed antenna coverage (polar diagrams)
- Antenna/system range
- Lightning strike (direct and indirect effects)
- Electromagnetic Pulse (EMP)
- Electrostatic Discharge (ESD)
- Electromagnetic Compatibility (EMC) and High Intensity Radiated Field (HIRF) threats

Our engineers have wide experience using electromagnetic modelling on many practical products (now certified and in service) in all parts of the product life-cycle, including concept, design, certification and through-life support.

Computational Electromagnetics High Performance Computing

Large parallel super-computers are required for the grand-challenge scale of processing required for whole vehicle, high fidelity simulations. The facilities are dedicated to electromagnetic computer analyses as these tend to involve long run-times which are incompatible with multi-user shared resource environments. The most powerful facility currently available is:

HP/Quadrics Cluster:

- 64 compute nodes each containing dual AMD Athlon 64 -bit quad core processors giving a total of 512 cores
- 1.5 TByte core memory
- Quadrics QSNet II high performance interconnect

POINT OF CONTACT

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A.3.2 Antenna Design and Testing Group

TEST RESOURCE CATEGORY

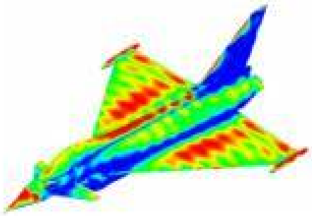
Primary: M&S / Other: N/A.

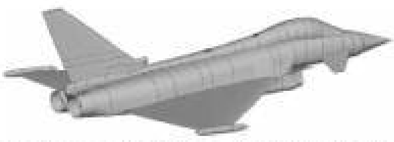
LOCATION

Alenia, E3 -Avionic Systems and Laboratories, Turin, ITALY.

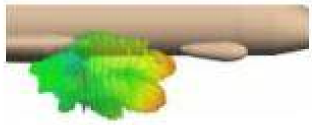
NARRATIVE DESCRIPTION

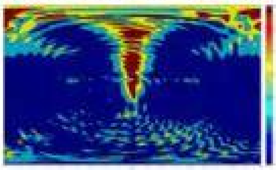
The Group is involved in the analysis of the antenna performance installed on Alenia platform, using the commercial state-of-art computational tools based on the principal frequency and time domain techniques to solve Maxwell's Equations. Electromagnetic problems are solved with a dedicated network of nine 64-bit workstations, with 640 GBytes of core memory that can manage multi-processor computations.

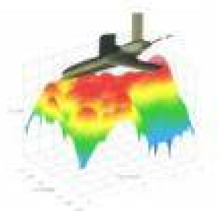


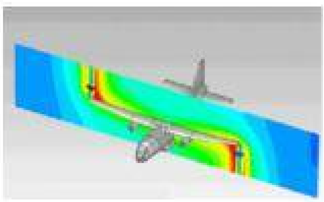


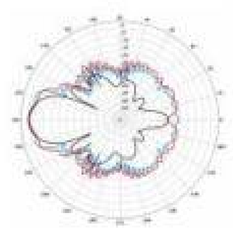
The tools are able to import directly the Computer-Aided Design (CAD) files, including cable routing and material proprieties, that the engineer experts will correct in an accurate and reliable model, from an Electromagnetic (EM) point of view. The main activity of the group deals with aircraft EM design: antenna siting aiming to ensure properly positioning of antennas on platform fuselage and to minimize/control unwanted EM interference between on-board transmitters and receivers, taking into account all aircraft mechanical constraints. Antenna to Antenna Coupling values, Antenna Radiation Patterns and Antenna Near Field Iso-Surface values can be numerically calculated, visualized and exported for further post-processing analysis. During and after design phase, confidence and accuracy of computational results can be assessed by performing only a small set of representative measurements, using computational predictions as a starting point for informed and efficient measurement preparation and planning. The HW computational capability allows the performance of parallel processing for overcoming all of the most demanding electromagnetic problems, such as evaluation of Radar Cross-Section at air vehicle level.











CAPABILITY SUMMARY

Electromagnetic Software Tools: Almost all of the state-of-art EM numerical tools are available for Antenna Design and Testing group. Electromagnetic techniques/codes available are reported in the following: • Method of Moment (MoM) • Multi-Level Fast Multiple Method (MLFMM) • Finite Element Method (FEM) • Boundary Element Method (BEM) • Finite Differential Time Domain (FDTD) • Approximate EM formulations such as Physical Optical (PO), Geometrical Optical (GO), Uniform Theory of Diffraction (UTD), Physical Theory of Diffraction (PTD), Large Element PO (LEPO) • Hybrid formulations such as MoM/PO, MoM/GO, MoM/UTD, MoM/PTD, MLFMM/LEPO, FEM/MLFMM, MoM/MLFMM • Shooting Bouncing Ray (SBR) and incremental length diffraction coefficient algorithms for radar cross-section analysis
Applications Antenna engineering expert use the HW and SW facilities to solve a wide variety of electromagnetic problems • Antenna design • Antenna placement (coverage) • Antenna-to-antenna coupling • RF interoperability analysis • Lightning strike (direct and indirect effects) • Bidirectional cable field co-simulation • Electromagnetic Compatibility (EMC) and High Intensity Radiated Field (HIRF) The available computational tools and the know-how engineers acquired in several years allow to adequately solve complex electromagnetic problems: in the last years the major activity has been the antenna placement. Now, group is able to predict global electromagnetic aircraft environment.
Computational Electromagnetic Computing Dedicated network of 64-bit workstations are used to solve electromagnetic problems, guaranteeing good accuracy and confidence between calculated results and measured value. The most powerful facility currently available is: **HP/Dell Network:** • Eight 64-bit workstations, dual-quad core Intell, with a total of 64 processor and 512 GByte of core memory • One 64-bit workstation, dual-quad core Intell, with 128 GByte of core memory

POINT OF CONTACT

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Email: ibertino@alenia.it
A Finmeccanica Company

A.3.3 Cassidian Computational ElectroMagnetics

TEST RESOURCE CATEGORY

Primary: CEM.

LOCATION

CASSIDIAN, Manching, GERMANY.

NARRATIVE DESCRIPTION

Cassidian has a custom 3D numerical simulation capability, for the full spectrum of electromagnetic applications, including antenna design and integration, for military, space and civil applications.

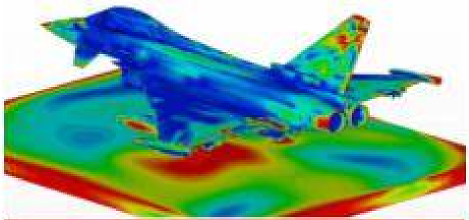
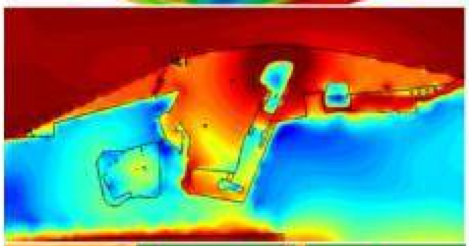
In support of this, a highly professional EM numerical tool set and high performance simulation computer hardware are available.

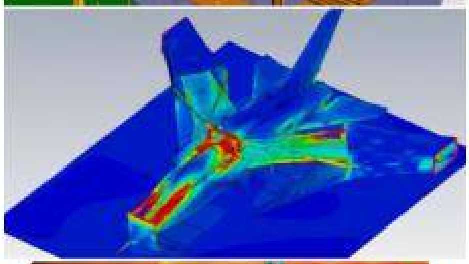
Computational EM Analysis is useful when measurements are not possible or practical with respect to time or costs, or when EMC tests (e.g., RE, CE, RS, CS) have FAILED and no solution was found, or when extremely high requirements exist with respect to Radiated or Conducted Emissions, as well as when EMC confidence is required to show compliance before prototyping.

CEM is also useful when Antenna performance needs be optimised for maximum operating distances, or for assessing whether commercially available antennas are suitable for specific applications, or when the antenna measuring equipment and/or expertise is not locally available.

Cassidian has substantial experience in 3D numerical simulations on advanced fighter A/C and other systems, in the prediction of very complex electromagnetic coupling behaviour.

Programs already supported include the Eurofighter TYPHOON, the Panavia TORNADO, the C-160 TRANSALL, and the P-3C ORION CUP.




CAPABILITY SUMMARY

Application Examples • Radiated emissions from electronic equipment • Shielding effectiveness • Lightning analysis for direct and indirect effects • Lightning zoning of all kind of vehicles • Determination of unknown electromagnetic resonances based on current distribution analysis, with all kinds of materials, e.g., metal, carbon, composites, plastics. • Verification of protection measures against all kinds of EMC related threats, such as conducted susceptibility (CS-XX), radiated susceptibility (RS-XX), LEMP and NEMP • Antenna design, e.g., thin-film conformal annular slot antennas • Antenna modelling of the radiation characteristics where measurements are not practical • Access to non-destructive, 3D X-ray scanning • Human safety: Definition of safety zones for high-power transmitters • Disguised antennas: Adaptation of antenna designs to hide them in structural parts • Performance simulation in specific environments, e.g., behind a radome • Co-site interference analysis, decoupling and spectrum management • Link predictions based on 3D wave propagation analysis
Electromagnetic Software Tools • FEKO – Method of moments, MLFMM, FEM, GO, PO, UTD • CST Microwave Studio – Finite Integration Technique and other EM solvers • ASERIS BE/FD – Boundary Element Method with GUI, Finite Difference Time Domain with GUI, Mesher • Wireless Insite – Uniform Theory of Diffraction + empirical models for wave propagation analysis • Hypermesh – CAD Meshing • E3-Expert – Interference analysis tool
High Performance Computational Electromagnetics Computing Facilities • 2-Node High-Performance Cluster (4 x Xeon Hexa-Core CPUs, 24 Cores @ 2.7 GHz, 384 GB RAM, ≈ 400 GFLOPS) • 4-Node High Performance Cluster (8 x Xeon Quad-Core CPUs, 32 Cores @ 3 GHz, 284 GB RAM, ≈ 600 GFLOPS) • 4-Node Cluster (4 x Xeon Dual-Core CPUs,16 Cores @ 3 GHz, 64 GB RAM)

POINT OF CONTACT

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A.4 SYSTEM INTEGRATION LABORATORY

A.4.1 Integration Facility for Avionic Systems Testing

TEST RESOURCE CATEGORY

Primary: SIL / Other: M&S, HITL.

LOCATION

Edwards Air Force Base, California, USA.

NARRATIVE DESCRIPTION

The System Integration Laboratory (SIL) is a flyable F-16 cockpit and simulation dome with significant Hardware-In-The-Loop (HITL) environment and open-air capability. This spread bench test environment provides Test Pilots and Engineers with a safe and effective environment for system evaluation and training. This unique capability also supports integration of new development items such as targeting pods, tactical data links, weapons, sensors and other items. Available spectral environments include Radio Frequency (RF), Electro-Optic (EO), Infrared (IR), and Electromagnetic Support Measures (ESM). The SIL supports Developmental Test (DT), Operational Test (OT) and other special test activities as determined by its customers.

Manned Flight Simulation (MFS) provides pilots and engineers capabilities to train and assess weapon systems during initial development, or in sustainment and modernization activities. Aircraft representative cockpits and displays are mechanized with aircraft Operational Flight Profile (OFP) software, driven by functional simulations to provide flight dynamics and/or avionics stimulation. High resolution and 360 degree horizontal / 240-degree vertical field of regard out-the-cockpit video provide a realistic environment to exercise weapon system capabilities. MFS provides the USAF and its contractors with a safe and effective environment for familiarization, develop flight profiles and test event timing, develop detailed test card procedures, and develop and debug aircraft systems, mature flight test procedures and timing, and assess weapon system performance. MFS supports Developmental Test (DT), Operational Test (OT) and other special test activities as determined by its customers.

CAPABILITY SUMMARY

SIL Capabilities	SIL Configurations

• Human factor interface
• Flight safety evaluations (i.e., ground collision avoidance)
• Mission development and rehearsal
• Full avionics system test
  • Avionics suite integration/testing
  • Line replaceable unit level testing
  • Anomaly investigation
  • Communications, navigation, ID
• Sensor integration
• EW blue/red man-in-the-Loop stations
• Weapons simulation, integration, and testing
• Digital bus and video data retrieval
• Crewmember/engineer familiarization/training
• Distributed linking (situational awareness)
• Tactical data links: Link-16, SADL, IDM
	• F-16 Cockpits (complete avionics hardware suite supporting Blocks 30, 40, 50, M3 and M4 architectures)
	• APG-68 Radar operators console
	• Link-16 landline or open-air
	Environmental Simulations
	• Fog
	• Time-of-day
	• Pressure/temperature altitude variations
	• Flat or spherical earth coordinate system

Mission Threat Environment The SIL can be linked with the Digital Integrated Air Defence (DIADs) simulation to provide an enemy air defence threat environment. The DIADs includes air interceptors, radar posts, GCI positions, filter centers and command post simulations with real operator in the loop capability. Other threat capability features include: • Graphically displayed air-to-air and air-to-ground targets and threats • Synthetic target sensor models to support Targeting Pod (TGP) and Fire Control Radar (FCR) • Synthetic RF target generation for stimulating actual radar systems • Combat Electromagnetic Environment Simulator (CEESIM) RF threat generation	
MFS Capabilities **Flight Sciences** • Envelope expansion • Flight control failure • Flight dynamics • Human factors with integration studies • Emergency procedures • Sensitivity analysis • Mission rehearsal	**Environment Conditions M&S** • Ownship winds • Fog/clouds • Rain/snow • Lighting with communication degradation • Time-of-day with sun/star positions • Sea states • Pressure/temperature altitude variations • Flat or spherical earth coordinate system

POINT OF CONTACT

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Edwards AFB, CA 93524-8210, USA
Tel: 661-275-7615 (DSN 525)

A.4.2 Portable Seeker/Sensor/Signature Evaluation Facility

TEST RESOURCE CATEGORY

Primary: SIL / Other: N/A.

LOCATION

Eglin Air Force Base, Florida, USA.

NARRATIVE DESCRIPTION

The Portable Seeker/Sensor/Signature Evaluation Facility (PSSSEF) provides several different flexible airborne and ground instrumentation platforms that can host an interchangeable mix of instrumentation that allows full characterization of surface and airborne targets. Hi-fidelity target signatures are critical for seeker/sensor development, guided weapons evaluation via simulated engagements, and live fire target validation. Measured target signatures are used to develop and validate digital signature models for hi-fidelity simulated weapons engagements. For example, IR and EO models can be provided in SPIRITS, CHAMP, and Real-Time CHAMP (RTC). The PSSSEF can collect and provide data in a wide variety of test scenarios including: simultaneous multi-spectral measurements of ground, sea, and airborne targets; measurement and characterization of aircraft flares and decoys; measurement of transmission, attenuation and backscatter of aerosols, obscurants and chaff; radar cross-section measurements of sub- or full-scale vehicles; characterization of radar absorbing material performance; background clutter measurements; antenna gain pattern measurement; and the effects of battlefield smoke, dust and chaff on C3I systems. PSSSEF provides signature measurements across the full operational spectrum including infrared, ultraviolet, visible, RF/millimeter wave, acoustic, seismic, and magnetic and can perform a full complement of measurements providing temporal, spatial, spectral, SAR/ISAR, LADAR, and calibration data. Several airborne carriage platforms are available including an F-15 for sub-sonic and supersonic carriage, a UH-1N Helicopter, and a Beech 18 aircraft. Ground facilities include the 300 ft Santa Rosa Island tower for land, sea, and air measurements, the 300 ft Seeker Test and Evaluation Facility (STEF) tower, and various test vans and trailers.

CAPABILITY SUMMARY

 *300 ft Open-Air Simulation Tower on Santa Rosa Island*	 *Seeker Test and Evaluation Facility*
IR/UV/Visible Measurements • Temporal, spatial, spectral • 1.5 – 3 microns • 3 – 5 microns • 8 – 12 microns • 263 – 281 nm (UV) • Visible	***RF and Millimeter Wave (MMW)*** • Ground, tower, and airborne-based systems • 10, 35, 95 GHz
Key IR/UV/Visible Instruments • STIRRS – Staring IR Radiometric System • ABSTIRRS – Airborne Staring IR Radiometric System • CIGARS – Calibrated IR Ground/Airborne Radiometric System • ASIMS Airborne Spectral IR Measurement System • TELOPS – 320 x 256 Ft Imaging Spectrometer (3 – 5 microns) • FLIR Systems SC6000 Imaging Radiometers (640 x 480 long wave, mid wave, short wave, and near IR)	***Key RF and MMW Instrumentation*** • AMIRS (Advanced MMW Imaging Radar System): 7, 10, 17, 35, and 95 GHz • MROCS-2 – (MMW Obscurant Characterization Sys): 10, 35, and 95 GHz • Lynx: Ku-Band Synthetic Aperture Radar (SAR) on B-18 • MERAJS (MMW Emitters, Radars, and Jamming Sys) • MMS (MMW Materials Measurement Sys) • DEWSIM (Directed Energy Weapons Simulator) consisting of various high-power microwave sources

POINT OF CONTACT

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A.5 HARDWARE-IN-THE-LOOP

A.5.1 ECSEL

TEST RESOURCE CATEGORY

Primary: Hardware-In-The-Loop Ground Facility.

LOCATION

Naval Air Warfare Center Weapons Division, Pt. Mugu, California, USA.

NARRATIVE DESCRIPTION

Occupying 10,000 square feet of high security Radio Frequency (RF) shielded space, the ECSEL houses threat simulation, instrumentation, and computer resources required to perform developmental test and evaluation of new EW systems and techniques, integration of EW components and sub-systems, and testing of new software revisions for EW systems presently deployed. Commonality between simulations on the ECR range and in the ECSEL make the ECSEL an efficient facility for troubleshooting EW system problems revealed during flight test.

The test approach used in the laboratory is one that incorporates actual EW system hardware interacting with the threat simulator. The threat simulators operate in real time at actual frequencies and receiver power levels. Open-loop RF environment simulators provide high signal densities which model emitter characteristics of threat systems such as airborne, land-based, and shipboard radars, as well as active command guidance signals for missile systems. Closed-loop simulators provide high fidelity replication of complete radar directed weapons systems such that the effectiveness of active jamming responses can be measured. Closed-loop simulations also include missile hardware simulation for semi-active threat systems. A scenario control computer, with associated aircraft cockpit and flight controls, provides the means to coordinate the simulators and incorporate realistic flight dynamics in the test process. This allows the EW system to be "flown" in laboratory scenarios that represent the electromagnetic environment encountered in actual combat or scenarios that will stress the EW system to its limits.

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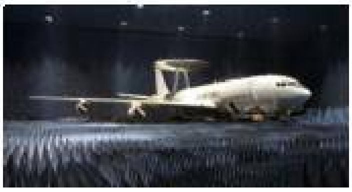
A.6 INSTALLED SYSTEMS TEST FACILITIES

A.6.1 Benefield Anechoic Facility (BAF)



TEST RESOURCE CATEGORY

Primary: ISTF / Other: MF, SIL, HITL.

LOCATION

Edwards Air Force Base, California, USA.

NARRATIVE DESCRIPTION

The Benefield Anechoic Facility (BAF) provides the installed system ground Test and Evaluation (T&E) element of the EW T&E process. This facility offers customers cost effective comprehensive ground test capabilities to thoroughly evaluate current and future complex, highly integrated, software-intensive avionics suites and EW systems installed on host aerospace platforms as well as ground-based platforms.

The primary purpose of the BAF is to test integrated avionics systems in a secure, controlled, and repeatable electromagnetically quiet environment using state-of-the-art simulation and stimulators that closely duplicate real combat mission environments. The test team also has collected, modeled, and generated high fidelity threat waveforms that are representative of the Open Air Range (OAR). It is also an ideal installed system test facility to evaluate performance and investigate anomalies associated with ground and airborne EW and avionics systems and tactical missiles and their host platforms.

Capabilities include simulation of airborne and ground-based threat radar, Communication, Navigation, Identification (CNI) simulation; radar target generator, GPS and GPS jamming; electromagnetic interference and compatibility testing and antenna pattern measurement and system of systems testing in a secure, dense environment.

The size of the large chamber also allows for far field RF radiation, thereby making most simulations much more accurate. The BAF is ideal for interoperability testing between multiple aircraft placed in the chamber simultaneously. The BAF supports Network Centric Operations testing with its ability to provide an electromagnetically dense threat environment coordinated with high bandwidth Link 16 test scenarios. The facility includes monitoring and instrumentation, two man-rated hoists, a turntable, interconnecting networks, a test control room, presentation rooms, and office space, and a small anechoic chamber for component tests. These laboratories can work autonomously or collectively to provide varying levels of test and analysis capabilities. All the laboratories are connected via a fiber optic network for communication, instrumentation, and data collection, monitoring and recording.

The Radio Frequency (RF) signal acquisition system provides independent measurement of all intentionally radiated RF emissions seen during testing. The signal acquisition system can provide both a near real-time analysis and a record of time sensitive, event driven, emitter activities and responses. These records include high resolution power, precision pulse-width, and accurate pulse interval measurements. The system is versatile enough to capture free space threat emissions or provide input ports to perform direct injections for source calibration or troubleshooting.

CAPABILITY SUMMARY

Benefield Anechoic Facility • Anechoic chamber and several shielded test laboratories • Offices, conference rooms • Secure facilities (tailored to program requirements)	**Chamber Dimensions** • Shield: 264 ft long x 250 ft wide x 70 ft high • Flight line door: 196 ft wide x 66 ft high • Three man doors

Support Services
• 175 ton 80 ft diameter turntable can rotate the system under test +/- 180 degrees at a 0.1 – 0.6 deg/sec.
• Two 40-ton hoists
• Aircraft electrical power:
  • 400 Hz, 115 VDC, 3Ø (General)
  • 270 VDC (Supports F-22 and JSF)
  • Support multiple aircraft simultaneously
• Instrumentation power: 28 VDC, etc.
• Cooling air: 6,600 CFM @ 10 PSI @ 30°F
• Hydraulic system: 4,000 PSI MIL-H-5606 and 83282
• Two Polyalphaolefin (PAO) Systems
RF Transmission and Reception
• Both free space radiation and direct injection capabilities are available
• Free space radiation has 20 RF generation carts arranged in the chamber to provide the desired sector and angle of arrival density
• Travelling Wave Tube (TWT) and solid-state amplifier configurations available
• Programmable, with control over all simulation and hardware functions. Scenario simulations are fully dynamic, providing for static or moving threats
• Direct injection capability provides various combinations of signal density and injection ports
• RF signal reception configuration:
  • All RF generation carts output monitored continuously
  • Chamber environment continuously monitored for SUT emissions and spurious signals
  • ECM response measurement
  • Threat simulator output verification
  • Chamber RF environment characterization
  • Integration of jammer pod response waveforms with a radar target return
	Shielding
	• Isolation: 100 dB 0.5 – 18 GHz
	• Quiet zone: 15 – 55' height x 209' x 180'
	  • -72 dB @ -0.5 GHz
	  • -84 dB @ 1 GHz
	  • -96 dB @ 2 GHz
	  • -100 dB @ 3 – 18 GHz
	• Anechoic frequency range: 0.4 – 18 GHz
	Instrumentation
	• Free space: 24-channel CEESIM MkN
	• Surface and airborne radars > 1000 simultaneous emitters
	• Dense threat environment (> 2 M pulses/sec)
	• High Fidelity Intrapulse Modulation (HFIM)
	• Provides pulse shaping capability every 15 ns
	• 21 channels with fast tuning synthesizers
	• 3 channels with slow tuning synthesizers
	• 2 amplifier configurations TWTA and SSA
	• Fiber optic connectivity to 20 carts which can be placed anywhere on the chamber floor
	• Frequency band 100 MHz – 18 GHz
	• Direct inject: 6 channels (amp and phase) CEESIM MkN
	• Designed for multiple port and channels configuration
	• Fast tuning synthesizers or digitally tuned oscillators
	• Frequency band 100 MHz – 18 GHz
	• Portable: 5 channels CEESIM MkN
	• Fast tuning synthesizers or digitally tuned oscillators
	• Frequency band 100 MHz – 18 GHz
	• Joint communication simulator system
	• Scenario based, complex RF signal generation system
	• Capable of creating a realistic, simulated RF environment comprised of thousands of CNI emitters/data links on thousands of platforms

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A.6.2 EW Test Facility (EWTF)

TEST RESOURCE CATEGORY

Primary: ISTF / Other: MF, SIL, HITL.

LOCATION

BAE SYSTEMS, Military Air Solutions, Warton, Lancashire, UK.

NARRATIVE DESCRIPTION

The EWTF complex comprises an aircraft-sized, RF- and laser-shielded anechoic chamber, shielded rooms, and an EW Sub-System Test Laboratory, all TEMPEST grade. It is co-located with the Division's Electromagnetic Engineering Department, who run the EWTF and other related M&S, MF, HTIL and SIL capabilities. Together, this whole-domain Electromagnetics Capability provides a flexible and reliable whole-life design and T&E service to military and other platforms. With EW T&E resources including state-of-the-art Combat Electromagnetic Environment Simulator (CEESIM) and Signal Measurement System (SMS)[1] for RF threat simulation and ECM response and analysis, other standard laboratory test equipment, and all necessary support infrastructure, the EWTF supports:

Free space chamber '*electronic battlefield*' testing of un-installed EW equipment, sub-systems, systems, and of installed EW systems on combat-sized aircraft and other platforms of similar size, in total electromagnetically secure conditions.

Direct signal injection and measurement testing of EW systems in a SIL/HITL environment.

The figure shows a selection of aircraft tested in the EWTF. The platform is immersed in a virtual battlefield for EW testing. Whilst primarily a 'drive in, drive out' EW ISTF, it is also used as an EW MF for installed antenna performance measurements, high intensity radiated field EMI/EMC testing, and full threat lightning testing. These are usually whole aircraft tests in the chamber, and the EWTF is simultaneously an EW MF and an Electromagnetics ISTF. The EWTF houses Computational Electromagnetics super-computers, the department's primary M&S capability. 1 – 18 GHz RCS measurements are also conducted in the chamber. These are described elsewhere in Annex A.

Selection of Aircraft Tested in EWTF
(© BAE Systems 2011, all rights reserved)

[1] CEESIM and SMS are Northrop Grumman Amherst Systems products.

CAPABILITY SUMMARY

EWTF Complex	**Anechoic Chamber Dimensions**
• Anechoic chamber and sub-system test laboratory • Offices, conference rooms, visiting team room • Secure vault (up to top secret; multi-Nation partitioned) • Peritrack access from EWTF to nearest runway	• Shield: 30 m long x 23.8 m wide x 13.5 m high • RAM-tip to RAM-tip: 29.1 m x 22.9 m x 12.5 m • Main door: 16 m wide x 12.5 m high • Two human-sized access doors, one double door
Shielding	**Support Services**

• Shielding > 100 dB from 10 kHz to 40 GHz
• TEMPEST grade, fully welded shield
• Quiet zone 18.2 m diameter, 9.5 m high
• Two quiet zone locations: centre and 4.7 m offset toward main door
• Quiet zone performance (up to 40 GHz):
  • Monostatic: -90 dB
  • Bistatic: -80 dB
• Laser/electro-optic/IR/UV testing: Class 4 laser-tight, double safety door interlocks
	• 70 tonne static capability
	• 30 tonne crane and 30 tonne turntable: independent and synchronised operation, 0.1 – 1.0°s-1 rotation rate
	• Sub-turntable laboratory and services room
	• Power: single/3∅ UK, 115/200 V 400 Hz 3∅ aircraft
	• Hydraulics: Max 280 bar, 180 litres/minute
	• Compressed air: > 10 bar, 22 m^3/minute
	• Static and mobile CCTV and video recording
	• Multi-zone fire detection and suppression:
	  • Smoke/heat, thermal cameras (RAM temperature)
	  • Water deluge: 1 ton/second for 3 minutes

RF Transmission and Reception	**Instrumentation**

• Six threat site multi-antenna stacks:
  • Four corners, at floor level; one at centre of wall opposite door; one at top of that wall
  • Steerable stacks, with laser pointer
  • Multiple transmit/receive antennas per stack
• Threat simulation configurations:
  • Basic: 21 TWTAs (microwave/millimetre wave)
  • Variety of other amplifiers, up to 1 – 18 GHz 1 kW CW and 9 kW pulsed (4%)
• Basic RF signal reception configuration:
  • ECM response measurement
  • Threat simulator output verification
  • Chamber RF environment characterisation
	• 11 channel CEESIM MkN:
	  • Microwave/millimetre wave channels
	  • 2 high speed synthesiser channels, 6 others available to be fitted as needed by test
	  • 256 emitters, 256 platforms, simultaneous at RF
	  • Modes: stand-alone, close-coupled and fully controlled by external control computer
	• SMS / Time synchronisation system:
	  • Wide-band, digitized IFM receiver
	  • Dual-channel, 80 MHz instantaneous bandwidth
	  • Extensive real-time/post-processing capability
	  • Event-driven signal capture
	• EW measurement system:
	  • Microwave/millimetre wave, 10 MHz bandwidth
	  • 25 MHz sampling ADC, 90 minute recording
	• Other: Microwave laboratory analysers, data

Further information: Pywell, M. and Midgley-Davies, M. Improved Test Capabilities for Cost-effective Performance Evaluation of Airborne Electronic Warfare Systems, J.RAeS, V.114, No.1158, September 2010.

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A.6.3 Air Combat Environment Test and Evaluation Facility (ACETEF)

TEST RESOURCE CATEGORY

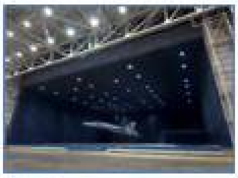
Primary: ISTF.

Location

Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, Maryland, USA.

NARRATIVE DESCRIPTION

The Integrated Battlespace Simulation and Test (IBST) Department, within NAVAIR, owns and operates the Air Combat Environment Test and Evaluation Facility (ACETEF). This fully integrated ground test facility supports Test and Evaluation (T&E) of highly integrated aircraft, weapon systems, and ground vehicles in a secure, controlled and electromagnetically quiet environment. ACETEF provides cost-efficient ground-testing capabilities for a multitude of programs across the DoD, commercial systems and aircraft.



ACETEF supports installed systems testing in a warfare environment using state-of-the-art stimulation and simulation technology. It also has a combination of laboratories that offer risk-reduction, compliance check and system performance for aircraft, their systems, and the warfighter. These laboratories provide realistic open-loop and/or closed-loop multi-spectral environment stimulation to Electronic Warfare (EW), sensor, communications, navigation and identification systems during both developmental and operational testing.

ACETEF is the T&E center of excellence for Modeling and Simulation (M&S) of the modern Battlespace environment behaviors and interactions. It provides credible, repeatable models of highly complex, interactive and reactive environments as well as scenario development and UAS expertise. The facilities utilize and support multiple warfare environment models and is the developer of two government-owned, license-free, mission-level models that support acquisition decision, warfare analysis, aircraft/aircraft systems, ground testing evaluation, and training.

ACETEF has the flexibility to create custom, real-time data displays and data gathering systems to aid customers in extracting the data they require from ground test events. The team's capabilities range from performing system simulation, providing ground-test support and stand-alone testing on installed aircraft Electronic Warfare (EW), Navigation (NAV), and Communication (COM) systems.

ACETEF operates a number of shielded and anechoic test facilities on the East and West Coast which provide a secure, uncontaminated RF environment to perform testing on installed avionics and handheld equipment. From a Boeing 707 sized aircraft to microchips, the facilities accommodate test vehicles at any size.

CAPABILITY SUMMARY

Shielded Hangar
- Has surrounding labs that provide uninterrupted realistic signals to systems under test
- Provides a controlled, secure and realistic test environment for system stimulation
- Accommodates multiple platforms
- Built to accommodate multiple large aircraft
- Wire mesh covered doors and walls, enabling Electromagnetic Environmental Effects (E3) testing, TEMPEST and COMSEC certification, and electronic warfare suite integration
- Provides a secure and realistic test environment for system stimulation
- Has access to three major runways

Aircraft Anechoic Test Facility (AATF)
- 100'L x 60'W x 40'H
- Designed for tactical size aircraft and helicopters
- Overall signal attenuation in the chamber is greater than 100 dB over a frequency range of 140 kHz to 40 GHz
- Has surrounding labs that provide uninterrupted realistic signals to systems under test

Advanced Systems Integration Laboratory (ASIL)
- Anechoic Chamber test Area: 180'L x 180'W x 60'H (32,000 square feet of floor testing area)
- Can accommodate two tactical aircraft (up to 40 tons) or one E-6 or Boeing 707 sized aircraft.
- Chamber isolation (15 kHz – 40 GHz) is specified as 100 dB. Maximum reflectivity of the RAM varies from -3 dB at 30 MHz, to -45 dB at 37 GHz.
- "U-shaped" pit under the chamber floor for stimulation equipment; signal cables are passed through ports in the floor
- Preparation area between chamber door and weather door keeps temperature on chamber door steady to prevent warping and provides additional area for testing
- The Operations Control Center (OCC) provides an area where tests can be controlled and viewed and is accessible to networks, simulator displays and SUT cameras

Electromagnetic Interference (EMI) Chambers
- 3 full anechoic chambers
  - 20' x 15' x 10'
  - 24' x 20' x 10'
  - 24' x 15' x 10'
- 1 mode stir chamber
- 20' x 16' x 10'

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A.6.4 Electromagnetic Test Capability

TEST RESOURCE CATEGORY

Primary: ISTF / Other: MF.

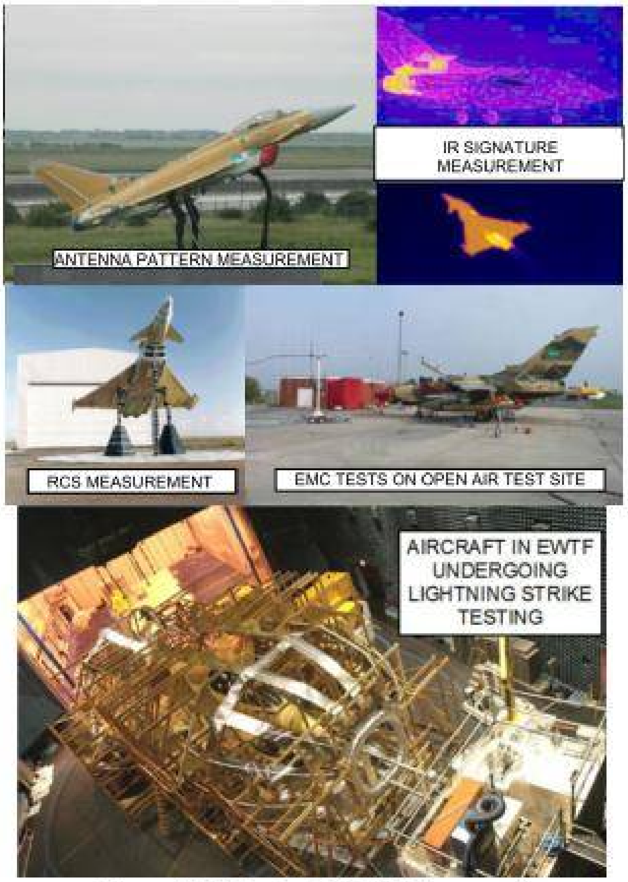
LOCATION

BAE SYSTEMS, Military Air Solutions, Warton, Lancashire, UK.

NARRATIVE DESCRIPTION

The Electromagnetic Test Capability spans the disciplines of EM Hazards (EMC/EMI), Lightning strike simulation, Signatures (RCS/IRS) and Installed Antenna Testing. To allow realistic full threat testing of whole aircraft platforms the ISTF includes a dedicated outdoor High Intensity RF (HiRF) Radio Environment Generator (REG) facility, a low power CW swept illumination facility for platform characterisation, a RF- and laser-shielded anechoic chamber (used for both HiRF and lightning strike testing), along with an outdoor RCS range. Additionally a range of smaller laboratories, some RF screened, are available for component and sub-systems testing.

The key benefit of most of the facilities is the ability to 'drive in' fully integrated platforms, from small UAVs to large combat aircraft. In particular the ability for many of the facilities to support platforms fully powered with 'live' Flight Control Systems and engines on, provides the most representative ground test environment. The figures show tests being performed in the various test facilities. The majority of the test capability has been developed with mobility in mind and testing has been performed around the World. With this mobility it is possible to test larger platforms on open field sites, customer bases and in hangars.



CAPABILITY SUMMARY

EM Hazards EMH/EMI

REG Facility Equipment

16 kW solid state 10 kHz – 200 MHz CW amplifier
1 kW solid state 100 – 1000 MHz CW amplifier

- Up to 50 V/m 5 – 30 MHz (at 15 m)
- > 200 V/m 30 – 200 MHz (at 5 m)
- > 450 V/m 200 MHz – 1 GHz (at 1 m)
- Targets up to 15 m

Microwave Test Capability

Minimum CW Capability	
Frequency (GHz)	Minimum Field Strength Level (V/m)
1 – 18	614

Minimum Pulsed RF Capability			
Frequency (GHz)	Peak Field (V/m)	PRF (kHz)	Pulse Width (μs)
1 – 2	2000	1	30
2 – 4	3883	1	25
4 – 8	3883	1	25
8 – 12.4	5000	1	30
12.4 – 18	2000	1	30

- Low Level Swept Characterisation (LLSC) 2 MHz – 400 MHz
- Bulk Current Injection (BCI) 2 – 400 MHz
- Bay attenuation 200 MHz – 18 GHz

Signatures (RCS/IRS)

RCS Measurement Range

- 2 – 18 GHz frequency coverage
- Full polarisation H, V and cross-polar
- Absolute RCS data, 1D and 2D imagery
- Platforms/targets up to 35 tonnes
- Targets up to 15 m in extent
- 7 m tall, 12 tonne Az/El low-RCS positioner

Mobile RCS Measurement System

- 2 – 18 GHz frequency coverage
- Test articles from component to whole body targets of 12 m in size
- Measure target in early and mid lifecycle, production stage and in service

IRS Measurements

- MWIR (1.5 – 5.5 μm) and LWIR (7 – 11.5 μm) thermal imaging cameras
- Measurements from -20°C to +1500°C
- Ground-to-ground, ground-to-air, air-to- ground and air-to-air capabilities
- Building/industrial equipment thermal surveys

Installed Antenna Pattern Measurements

- Use of outdoor RCS range
- 360 degrees turntable
- Performance verification of:
  - Direction of Arrival (DoA)
  - Effective Radiated Power (ERP)

Lightning Strike Simulation

- Any arbitrary shot amplitude from 200 kA full threat down to 20 kA sub-full threat
- Aircraft return conductor solutions up to 40 m x 40 m
- Anechoic chamber solution for platforms up to 16 m wide and 12.5 m high

Microwave Materials Measurement

- 100 MHz – 20 GHz frequency coverage
- Co- and cross-polarisations, complex relative permeability and permittivity, reflectivity
- S-parameters and surface wave attenuation
- 7 mm co-axial, free-field focussed beam, open-ended co-axial probe and NRL arch

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A.6.5 Anechoic Shielded Chamber

TEST RESOURCE CATEGORY

Primary: ISTF / Other: MF.

LOCATION

Alenia Aeronautica S.p.A., Caselle South Plant, Turin, ITALY.

NARRATIVE DESCRIPTION

The Anechoic Shielded Chamber (ASC) is the Alenia Aeronautica state-of-the-art testing facility designed to perform Electromagnetic Compatibility measurements and High Radio Frequency (RF) Sensitivity tests in a protected environment from both RF external noise and adverse weather conditions.

The Anechoic Shielded Chamber is a fully anechoic facility that allows to perform, in a controlled environment, both Intra- and Inter-system, such as EMC and High Intensity Radiated Field verification, in a representative environment of free-space, i.e., equivalent to actual flight conditions, and according to applicable civil and military standards.

The ASC is also provided with equipment for performing Antenna Radiation Pattern measurements and is suitable for Electronic Warfare (EW) tests.

The Anechoic Shielded Chamber is included in the same Host Building with another major facility: the Sky Light Simulator, the most advanced aerospace lighting laboratory in the world.

The Anechoic Shielded Chamber is composed of four shielded environments: an Anechoic Shielded Chamber (ASC), a Shielded Control Room/Amplifier Room 1 (SCR/AR1), an Electronic Warfare Chamber (EWC) and a Reverberating Chamber.

A Preparation Room located in front of the ASC Main Access Door, represents a protection against atmospherics and a comfortable area for aircraft setting up before the test campaign.

Remote management of the Anechoic Shielded Chamber is possible inside the Shielded Control Room (SCR) where the test execution in comfortable, automatic and safe condition is assured by: HIRF power generation control and monitoring system, CCTV system equipped with five cameras installed at different height and an infrared camera.

The Anechoic Shielded Chamber is designed to perform EMC/HIRF and RF testing on fighter aircraft as Eurofighter, Tornado, M-346 but it is also suitable for: small civil aircraft, rotorcraft, spacecraft, EW pod and weapon system such as missile, ground vehicle and system. Moreover, the Anechoic Shielded Chamber is approved by the IT NSA as a TEMPEST test facility for platform/system.

CAPABILITY SUMMARY

Anechoic Shielded Chamber • Anechoic chamber and several shielded test laboratories • Offices, conference rooms • Secure facilities (tailored to program requirements)	**Chamber Dimensions** • Shield: 30 m long x 30 m wide x 20 m high • RAM-tip to RAM-tip: 26 m x 26 m x 16 m • Main door: 18 m wide x 8.5 m high • One 2.5 m wide x 2.5 m access door • One human-sized access door
Shielding • Shielding > 100 dB from 200 kHz to 18 GHz • TEMPEST grade, fully welded shield • Quiet zone 10 m diameter, 6 m high • Anechoic frequency range: 30 MHz -18 GHz	**Support Services** • 30 ton 10 m diameter turntable can rotate the system under test +/- 180 degrees up to 1 deg/sec. • One 25-ton hoist • Aircraft electrical power: • 400 Hz, 115 VDC, 3Ø (General) • Instrumentation power: 28 VDC, etc. • Cooling air system • Hydraulic system
EMI/HIRF • 10 kW solid state 9 kHz – 100 MHz CW amplifier • 4 kW solid state 100 MHz – 1000 MHz CW amplifier • 1 kW solid state 1 – 18 GHz CW amplifiers • 2 kW TWT 1 – 18 GHZ PW amplifiers • Low Level Swept Characterisation (LLSC) 30 MHz – 400 MHz • Bulk Current Injection (BCI) 10 kHz – 400 MHz • Low level swept field/bay attenuation 30 MHz – 40 GHz • Emission radiated and conducted test 2 MHz – 18 GHz	**Installed Antenna Pattern Measurements** • NF-FF test facility using spherical • Performance verification of: • Effective Radiated Power (ERP) **Microwave Materials Measurement** • 100 MHz – 20 GHz frequency coverage • Co- and cross-polarisations, complex relative permeability and permittivity, reflectivity • S-parameters and surface wave attenuation

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A Finmeccanica Company

A.6.6 Electromagnetic Open Area Test Sites

TEST RESOURCE CATEGORY

Primary: ISTF / Other: MF.

LOCATION

Alenia Aeronautica S.p.A., Caselle South Plant, Turin, ITALY.

NARRATIVE DESCRIPTION

The **Electromagnetic Test Centre** is mainly involved in ElectroMagnetic Compatibility / High Intensity Radiated Field (**EMC/HIRF**) qualification and certification of aircraft products that Alenia Aeronautica designs autonomously, such as the last generation of UAV technological demonstrators Sky-X and Sky-Y or, more frequently, in partnership with other national or international aerospace industries. The most recent aircraft like C-27J Spartan, Eurofighter Typhoon and Alenia Aermacchi M-346 have been tested and certified by Alenia's Electromagnetic Test engineers using the **Open Area Test Sites** with proprietary test instrumentation.

The main activities of the Alenia Aeronautica **Electromagnetic Test Centre** are: to evaluate the electromagnetic compatibility and susceptibility aspects in system integration, to test and verify the satisfaction of EMC and HIRF requirements of complex platform, to perform final tests to demonstrate the fulfilment of International Standard requirements for Certification purposes, to test and check the RF performance of sub-systems integrated into air vehicle (e.g., navigation aids equipment), to test and check the performance of emitter devices directly installed on the aircraft (e.g., antenna radiation pattern), to support the testing activities defining the appropriate test instrumentation and facilities based on new testing requirements, to deal with EMC issues developing dedicated test instrumentation, new facilities and/or testing methods, with the aim to keep the technical know-how updated at the state-of-the-art.

The **EMC Test Range** is a dedicated open area (around 5,400 m^2) including two circular test areas of 15 m diameter for vertical and horizontal polarization HF radiation; the **EMC Test Range** is equipped with a turntable platform that allows full 360° aircraft rotation.

The **Transport Test Area** was built at the beginning of 2001 specifically for the certification of the C-27J transport aircraft. The result is a dedicated open area (50 m x 50 m), in which it was possible to perform the EMC tests with and without engines running that supported the civil certification of the C-27J in June 2001.

Various **Mobile Test Stations** are working in both OATS, each provided with RF instrumentation, tools and PCs to conduct EMC/HIRF testing in flexible, comfortable and safe manner.

Both Open Area Test Site are equipped with all the necessary ancillary system to provide electrical and hydraulic feed to air vehicles during the measurement campaign.

CAPABILITY SUMMARY

Open Area Test Site: • Three testing locations for both horizontal and vertical polarization • Offices, conference rooms	**Test Site Dimensions:** • EMC Test Range: 5400 m^2 with two testing locations • Transport test aircraft range: 50 m x 50 m

EMI/HIRF:
• 20 kW solid state 1 – 30 MHz CW amplifier
• 10 kW solid state 9 kHz – 100 MHz CW amplifier
• 4 kW solid state 100 MHz – 1000 MHz CW amplifier
• 1 kW solid state 1 – 18 GHz CW amplifiers
• 2 kW TWT 1 – 18 GHZ PW amplifiers
• Low Level Swept Characterisation (LLSC) 1 MHz – 400 MHz
• Bulk Current Injection (BCI) 10 kHz – 400 MHz
• Low level swept field / bay attenuation 1 MHz – 40 GHz
• Emission radiated and conducted test 2 MHz – 18 GHz
	EMC Test Range Support Services
	• 30 ton 8 m diameter turntable can rotate the system under test +/- 180 degrees up to 1 deg/sec.
	• One 25-ton hoist
	• Aircraft electrical power:
	  • 400 Hz, 115 VDC, 3Ø (General)
	• Instrumentation power: 28 VDC, etc.
	• Hydraulic system
	• Ground plane
	• Wooden platform (h 3.0 m)
	• Fixed antennas (5 ÷ 30 MHz)
	• Mobile antennas (30 MHz ÷ 40 GHz)
	• Shielded test stations
	
	Transport Test Range Support Services
	• Aircraft electrical power:
	  • 400 Hz, 115 VDC, 3Ø (General)
	• Instrumentation power: 28 VDC, etc.
	• Hydraulic system
	• Dedicated trolley for aircraft rotation
	• Fixed antennas (2 ÷ 30 MHz)
	• Mobile antennas (30 MHz ÷ 40 GHz)
	• Shielded test stations

POINT OF CONTACT

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A Finmeccanica Company

A.6.7 USAF Joint Pre-Flight Integration of Munitions and Electronic Systems (J-PRIMES)

TEST RESOURCE CATEGORY

Primary: Installed Systems Test Facility (ISTF).

LOCATION

Eglin AFB, FL, USA.

NARRATIVE DESCRIPTION

The J-PRIMES anechoic chamber, as an Installed Systems Test Facility (ISTF), provides testing of air-to-air and air-to-surface munitions and electronics systems on full-scale aircraft and land vehicles prior to open air testing. Through simulation and modelling, vast amounts of performance data can be obtained at a fraction of the time and cost of conventional flight test programs alone.

(Image: USAF/Samuel King Jr.)

CAPABILITY SUMMARY

J-PRIMES Provides The Following Major Test Areas:

RF Anechoic Chamber

- 100 dB RF-isolated anechoic chamber with a hoist lift capacity of 40 tons and capable of testing all current USAF, USA, and USN fighter aircraft and helicopters, a variety of ground combat vehicles, and numerous commercial platforms

Outdoor Ramp

- Open-air flight line area for testing of large aircraft, with access to all facility simulation and instrumentation

Test Stations

- Shielded laboratories for sub-system level testing of fighter and bomber electronics and weapon systems

EMI/EMC Chamber

- Semianechoic shielded enclosure for testing of MIL-STD 461/462 and many other EMI/EMC commercial specifications

J-PRIMES Instrumentation Includes:

- AMES II for simulation of threat radar signals
- Four target, closed loop radar target simulator with dynamic radar cross-section, jet engine modulation, electronic countermeasures, and clutter signatures used to simulate threat engagement scenarios
- MIL-STD-1760 weapons and aircraft simulator for interfacing with aircraft systems
- Two 10-channel differential GPS constellation and GPS jammers

POINT OF CONTACT

J-PRIMES
46 RANG/TSPA
401 W. Choctawhatchee Avenue, Suite 263
Eglin AFB, FL 32542-5724, USA
Tel: 850-882-8472 or 850-882-8102
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Fax: 850-882-8162

A.6.8 CASSIDIAN EME Test Facility

TEST RESOURCE CATEGORY

Primary: ISTF: Whole System EM Testing.

LOCATION

CASSIDIAN, Manching, GERMANY.

NARRATIVE DESCRIPTION

The Cassidian EME Test Facility is a full threat level, 5 – 30 MHz HIRF test facility and provides individually tailored testing for EME qualification, verification and certification support for military and civil customers, for large and operational systems.

EME testing is performed according to national, international, military, NATO and civil standards, as well as customer defined requirements. Supporting activities such as test definition, test vehicle monitoring and data evaluation are available.

An RF transparent, rotatable, heavy duty wooden lifting platform is available to eliminate ground effects and to ensure a large and homogeneous test volume. Additionally, mobile HIRF test facilities up to 18 GHz are available, to support on site testing at customer locations. The facility has excellent antenna decoupling and interference measurement capabilities. State-of-the-art Test Equipment is used throughout.

EM Testing is typically performed when the certification authorities require re-testing due to modifications on a system (e.g., due to changes in cabling, new electronic/electrical equipment, changes due to obsolescence), or when a type certification of a system or sub-system is required by the certification authorities, or when an engineering test is required to reduce the risk due to EMC related failures, as well as when EMC failures have occurred during normal operation.

Some of the systems already tested include the Eurofighter TYPHOON, the Panavia TORNADO, the F-4F PHANTOM, the C-160 TRANSALL, the P-3C ORION CUP, as well as the NH90 TTH and the CH53GA helicopters.

CAPABILITY SUMMARY

Application Examples
- Small to large system testing, with mobile test equipment
- Type certification for German flight clearance authorities (ML)
- Shielding effectiveness measurement of all kinds of objects
- Conducted and radiated emission measurements of all kinds of objects, including with running engines
- Antenna pick up, noise, phase decoupling and installed performance measurements
- Direct (DCI) or indirect current injection into all kinds of structures

Electromagnetically Transparent Wooden Elevation Platform:
- Raising of test objects up to 20 m into the homogenous zones of horizontal polarized EM fields
- Platform load max. 30 t, turn range ±182°
- Large test volume: Vertical polarised (40(l) x 35(b) x 12(h) m); Horizontal polarised 20 x 15 x 6 m

HIRF Test Capabilities
- 5 – 30 MHz up to 250 V/m (100 kW)
- 30 – 500 MHz up to 250 V/m (2 – 5 kW)
- 0,5 – 1 GHz up to 650 V/m (2 kW)
- 0,8 – 18 GHz up to 1000 V/m (350 W)

Direct Current Injection (DCI)
- To support low frequency HIRF testing on complex systems

Low Level Swept Current (LLSC) Testing
- 1 – 400 MHz, 64 current probes in parallel, ultra fast measurement technique

Low Level Swept Field (LLSF) Testing
- 5 MHz – 18 GHz, up to 12 field probes in parallel

Bulk Current Injection (BCI)
- 10 kHz – 400 MHz, multi-injection

Enhanced Level Injection into onboard sensors
- 10 kHz – 18 GHz, all modulation types

Standards
- All IEC, EN, DIN standards
- All MIL-STDs
- All VG standards
- All STANAG standards
- Customer specific

POINT OF CONTACT

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A.7 OPEN AIR RANGES, INCLUDING EW T&E FLIGHT TEST CAPABILITIES

A.7.1 Electronic Combat Range

TEST RESOURCE CATEGORY

Primary: OAR / Other: HITL.

LOCATION

China Lake, California, USA.

NARRATIVE DESCRIPTION

The Electronic Combat Range (ECR) is physically located in California at China Lake's South Range and provides a realistic electronic combat environment. ECR provides threat systems; operations and range control; instrumentation; Time, Space, Position Information (TSPI), telemetry, optical and communications; data processing and display systems; and signal monitoring, calibration systems and assessment and repair facilities for test and evaluation and training customers. The ECR is the Navy's principle open-air range for test and evaluation of electronic combat systems.

Threat Simulations

The ECR offers a wide variety of threat simulations, surrogates and actual systems, providing a threat-rich environment. The 1,200 square miles of restricted airspace overlying 900 square miles of Navy land offer ample room for either single- or multi-platform events.

Open-air hardware-in-the-loop testing at the ECR helps bridge the gap between laboratory and open-air testing. Long before a system is ready for flight testing, the hardware can be tested against an assortment of threat systems and advanced technology simulators.

Multiple threat systems are available: actual, surrogate and simulated. A broad range of EW technologies are offered: pulse, continuous wave, Doppler, multi-spectral, and Blue and Gray systems. Test emitter spectrums include radio frequency, electro-optical and millimeter wave. All systems use audio and video instrumentation to collect extensive digital flight test data.

Test Support

At ECR, aircrew have the opportunity in a single mission to combat both an air-to-air threat and a surface-to-air threat as well as complete an air-to-ground strike mission.

Top secret and special-access level security is available with minimum electromagnetic interference. ECR supports a combination of land and naval systems (littoral threat). The ECR provides engineering support, developmental and operational test and evaluation, analysis, and training resources for users of systems that counter or penetrate air defences.

CAPABILITY SUMMARY

Types of Events	Technologies
• Electronic Countermeasures (ECM) effectiveness testing • Radar Warning Receiver (RWR) testing • Unmanned Aerial Systems (UASs) • Expendables – chaff and flare effectiveness • Towed and air launch decoy testing • Anti-Radiation Missile (ARM) flight testing to evaluate seekers and avionics • Tactics development • Training	• Pulse systems • Continuous wave systems • Pulse Doppler systems
Data Outputs	**Systems Provided**
• Scope video • Boresight video • Display video • Radio recordings • Crew hot mike recordings • Digital data • Raw unprocessed data • Sorted corrected data (wild point flags and sorted by time)	• Advanced threat simulations • Surrogates • Red, blue, and gray threat assets

POINT OF CONTACT

Electronic Threat Systems
7000 Randwash Road
China Lake, CA 93555, USA
Tel: 760-939-5303
www.navair.navy.mil/ranges

A.7.2 Vidsel EW Test Range

TEST RESOURCE CATEGORY

Primary: OAR / Other: EW-Training Range.

LOCATION

Vidsel Test Range is located in the northern part of Sweden, almost on the Arctic Circle and close to Vidsel Airbase (ESPE).

NARRATIVE DESCRIPTION

Vidsel Test Range is operated by the Swedish Defence Materiel Administration (FMV) and is best known for its large overland capability and for its weapon employments. At Vidsel Test Range it is possible to undertake Air-to-Air firing with large stand-off weapons, to employ various live bombs and also to operate UAV flights.

In recent years EW has become a key factor in the development of the range. During the NATO Loyal Arrow exercise (2009) and in other international air exercises Vidsel Test Range has provided realistic EW threats. Since Vidsel Test Range and the surrounding Restricted Area is so large, vertically and horizontally, it's very well suited for large scale training or for tests that require large space.

The Swedish Armed Forces have performed tactical testing at Vidsel of their equipment and flight crews against IR/UV threat simulators.

Foreign air forces have conducted a tactical EW-training course with helicopters at Vidsel Test Range using generic RF threats as well as IR/UV simulators.

The Swedish aircraft industry has also used IR/UV simulators to do tests of Missile Approach Warning Systems (MAWS).

CAPABILITY SUMMARY

Range Area • The total range area where we can employ weapons is approximately 35 x 70 km and this area can be evacuated if needed.	**Airspace** • The Airspace (Restricted Area / ESR02) surrounding the range area is approximately 70 x 120 km laterally and unlimited vertically. Vidsel Test Range 'owns' the airspace which makes it possible to use the air very flexibly.
Infrastructure • Vidsel Test Range has excellent infrastructure with fibre and RF links, networks, road networks, electrical power networks, airfield, range instrumentation systems and much more. There is also a structure in which different kinds of threat systems can be connected in many various locations. This structure is connected to a real-time control system, VIEWS by CAS, UK, in the main mission control center. Post mission evaluation (quick feedback to air crews) is also done in/with this system.	**Airbase** • Vidsel Test Range is supported by Vidsel Airbase (ESPE) located approximately 30 km from the southeast corner of the Range Area. The airbase is fully operational with a 7300 ft runway equipped with an arresting cable. **IR/UV** • Vidsel Test Range has two Mallina systems which simulate IR/UV threats (SA-7). These simulators are very flexible for use as tactical threats and can also be used to verify MAWS and flare systems.
RF • Vidsel Test Range can offer three tracking radar units as generic RF-emitters for testing or tactical training.	**Flares** • Vidsel Test Range allows the use of flares at all levels in the range area (depending on the level of fire hazard).
Chaff • Vidsel Test Range allows the use of chaff.	**EW-Jamming/GPS-Jamming** • Vidsel Test Range allows EW and GPS jamming (subject to approval from the authorities).

POINT OF CONTACT

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A.7.3 Center for Countermeasures (CCM)

TEST RESOURCE CATEGORY

Primary: OAR / Other: N/A.

LOCATION

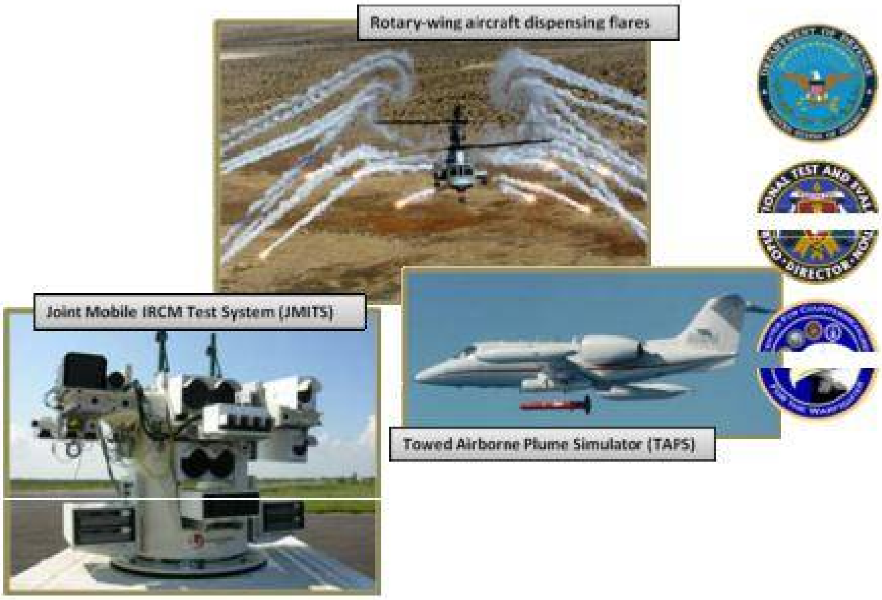
White Sands Missile Range, New Mexico, USA.

NARRATIVE DESCRIPTION

The Center for Countermeasures (CCM) directs, coordinates, supports and conducts independent Countermeasure (CM) / Counter-Countermeasure (CCM) test and evaluation activities for U.S. and foreign weapon systems, sub-systems, sensors and related components. We are a tenant organization at White Sands Missile Range and report to and receive guidance and funding from the Office of the Secretary of Defense, Director, Operational Test and Evaluation.

The Center supports all of the Services and other federal agencies in their test activities by having world-class organization for open air IRCM T&E, providing Survivability Equipment (SE) with an emphasis on rotary and fixed wing platforms, providing Hostile Fire (HF) data collection and activity coordination, and offering threat injection during pre-deployment events.

The Center provides many unique capabilities including mobile, self-sufficient T&E equipment; zero labor cost providing significant savings to the program; independent CM/CCM assessments at anytime in the program's acquisition cycle; and establish and maintain US-NATO survivability memorandums of agreement.



CAPABILITY SUMMARY

Types of Events:	Technologies:
• Independent counter-countermeasure test and evaluation • Zero labor cost providing significant savings to the program • Independent CM/CCM assessments at anytime in the program's acquisition cycle • Establish and maintain US-NATO survivability memorandums of agreement	• Threat injection during pre-deployment events
Data Outputs:	**Systems Provided:**
• Hostile fire data collection	• Mobile, self-sufficient T&E equipment • Survivability equipment with an emphasis on rotary and fixed wing platforms

POINT OF CONTACT

Center for Countermeasures
Tel: 575-678-7200

A.7.4 NATO Joint Electronic Warfare Core Staff

TEST RESOURCE CATEGORY

Primary: OAR / Other: N/A.

LOCATION

Main Operating Base is at RNAS Yeovilton, UK; however all assets are mobile and deployable as required throughout the NATO AOR.

NARRATIVE DESCRIPTION

NATO Joint Electronic Warfare Core Staff (JEWCS) has a number of functions including provision of a hostile EW environment in which to conduct training at the tactical and operational levels in the land, maritime and air environments for all NATO standing and assigned forces. (This includes a remit to support EW trials and experimentation). It also supports Operations, provides the NATO Emitter Database (NEDB) and provides NATO's core EW staff function, EW policy and doctrine.

The JEWCS EW training capability is applicable to EW T&E Flight Testing and can provide: Radar and communications emitter simulation, Radio communications intercept, jamming and deception, Radar jamming and deception, Datalink jamming and EMCON and COMSEC monitoring. These capabilities are provided by assets operating in the air sea and land environments, any of which could be utilised in Flight Testing. The fundamental difference between the JEWCS assets and those on a more traditional EW range is that the assets are all mobile or transportable and routinely deploy to the location required throughout the NATO AOR. It should be noted however that because of equipment limitations and training artificialities the power levels of the equipments are not calibrated and are not usually representative of operational systems.

A brief description of the EW assets is as follows:

- **EW Pods** – ALQ-167 pods which can be carried on contractor business jet type aircraft such as DA-20 Falcon or Learjet, or on suitably certified fast jets, currently only F18, F4 and Hawker Hunter. 8 radar simulation pods and 24 Jamming pods. Effective for both air to air and air to ground jamming and Simulation.
- **TRACSVANs** – (TV) Transportable Radar and Communications Jamming and Simulation Vans TV. Optimised for maritime EW but also usable in other scenarios. They are capable of simultaneous radar jamming, radar simulation, datalink jamming and communications jamming/deception. The TV can be deployed at sea on host-ships or can deploy on land operating off a transporter. Capable of ground to air, although for radar jamming and simulation it has very limited capabilities for optically tracking fast moving (airborne) targets.

- **MINI-RADARVAN (MRV)** – Vehicle capable of radar simulation and jamming, including DRFM. Capable against surface or airborne targets; however it is primarily intended for use against fixed surface targets, tracking capability is very limited.

- **SHORT RANGE AIR DEFENCE SITE SIMULATOR (SAD)** – Capable of simulating radars associated with Surface-to-Air Missile systems or Anti-Aircraft-Artillery systems. Targets are acquired and tracked visually through binoculars.
- **UV MALLINA SYSTEM (MALLINA)** – Capable of short range stimulation of UV Missile Warning Systems.
- **NATO EW VANs (NEWVAN – NV)** – Optimised for Land EW, but also usable for amphibious and air exercises. Provides Comms ESM, jamming and deception.

- **NI NEWVAN (MNV)** – Landrover-based capabilities similar to NV.
- **MOBILE INTERCEPT JAMMING ASSETS (MIJA)** – Off-road capable communications assets which can provide ESM intercept, jamming and deception.

CAPABILITY SUMMARY

- ALQ-167 pods.
- Simulation:
  - Banded frequency range: 7.8 to 17.5 GHz, PRF 200 – 6000, PW 0.1 to 2.0 µSec, stable, jittered and staggered PRF modes. Jamming: noise and coherent (DRFM) techniques. Banded frequency range: 0.85 to 17.2 GHz.
- MRV radar simulation and jamming (non-coherent and coherent techniques) 0.85 GHz – 18 GHz. V/UHF comms.
- SAD. Bands 7.8 – 8.5, 8.5 – 9.5 and 14.5 – 15.2 GHz. PRF 200 – 5500 (stable or random jitter or stagger).
- UV Mallina. Library modes for test MAWS/DASS (AN/AAR-47, AN/AAR-54, AN/AAR-57, AN/AAR–60, MAW-200)
- NEWVAN, Mini NEWVAN and MIJA. Surveillance/DF 2 – 1000 MHz, Jamming 2 – 1000 MHz (capabilities vary)

POINT OF CONTACT

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A.7.5 T&E Support for Aircraft Survivability

TEST RESOURCE CATEGORY

Primary: OAR / Other: N/A.

LOCATION

Eglin Air Force Base, Florida, USA.

NARRATIVE DESCRIPTION

The 46th Test Wing (46 TW) provides complete end-to-end Test and Evaluation (T&E) capability for aircraft self-protection systems and threat system performance in support of aircraft survivability and vulnerability studies.

Extensive target signature measurement capability provides calibrated data across the full electromagnetic spectrum and operational environment. Flexible airborne and ground instrumentation platforms allow measurement of all surface and airborne targets. These target signatures are used to develop and validate digital signature models for virtual missile to target engagements. For example, simulated Infrared (IR) and Electro-Optical (EO) target models can be developed using Spectral and In-band Radiometric Imaging of Targets and Scenes (SPIRITS), Composite Hard-body and Missile Plume (CHAMP), and Real-Time CHAMP (RTC) software. Red and blue missiles seekers can engage these virtual targets in a non-destructive HITL simulation. With extensive land and water ranges and a wide variety of test instrumentation assets, the 46 TW provides a unique open-air capability to evaluate sensors and seekers against real-world targets in realistic air, land, and sea background test and training scenarios. Open-air assets include the Missile Warning Sensor Stimulator, the Seeker Test Van, the STEF, and a variety of flight certified pod-based platforms. The 46 TW has a great deal of experience planning and conducting tests of aircraft self-protection systems against heat-seeking missiles, and has been an instrumental team member in almost all major IR protection programs including: the Large Aircraft IR Countermeasure System (LAIRCM), the Directed IR Countermeasure System (DIRCM), Advanced Threat IR Countermeasures System (ATIRCM), and Advanced Strategic Tactical Expendable Program (ASTE). These programs span self-protection applications across many diverse types of aircraft and operational users.

CAPABILITY SUMMARY

SEEKER TEST VAN (STV) The Seeker Test Van (STV) is an aid in the development and exploitation of the Guidance and Control Units (GCUs) of ground-to-air and air-to-air missiles, the assessment of countermeasures effectiveness, techniques, and tactics in an open-air test environment. • Collects data on up to six GCUs simultaneously • Three seeker control stations (each controlling two seekers) • A data acquisition station, a video and data recording station, a data reduction station, and a mission control station • KTM has five mounting surfaces for seekers, visible cameras, Infrared (IR) cameras/radiometers, and a Mallina Missile Warning System (MWS) stimulator/simulator • Employs a missile roll fixture to create a realistic test scenario for rolling airframe missiles	 Typical instrumentation suite for testing aircraft missile warning systems
GUIDED WEAPONS EVALUATION FACILITY (GWEF) The GWEF provides multi-spectral simulations for test and evaluation of precision-guided weapons, threat systems, and countermeasure systems. A complete range of T&E capability is available including digital simulation, HITL simulation, parametric measurements, countermeasure testing, and performance characterization assessment. The GWEF is the only facility of its kind able to test the complete spectrum of weapon seekers and sensors under one roof. • Digital and Hardware-In-The-Loop (HITL) simulations of air armament munitions • Parametric measurements • Countermeasure (CM) testing • Directed Energy (DE) countermeasure effectiveness testing against MANPADS • HITL testing incorporates full imaging capability of aircraft targets via leading edge technology of resistor arrays • Provides virtual test range for multi-mode sensors including millimeter wave, imaging infrared, and semi active laser	 Simulated MANPADS trajectories with no countermeasures  Simulated MANPADS trajectories with active countermeasures
EGLIN MOBILE MISSILE LAUNCHER SYSTEM (EMMLS) EMMLS provides live launch capability for Man-Portable Air-Defence Systems (MANPADs) against real or simulated aircraft. • EMMLS consisting of a positioned, a control vehicle and a generator to power the system • EMMLS is capable of firing both foreign and domestic MANPADS • EMMLS operates both a generic positioner on a portable trailer for testing shoulder-fired MANPADS, and a simulated threat Transporter/ Erector/Launcher (TEL) for larger surface-to-air missiles • The control van operates the launchers and can record missile diagnostic signals, position information, video (infrared and visible), referenced to IRIG time	 Live MANPADS launch from EMMLS

POINT OF CONTACT

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A.7.6 Trials/Test Support Group

TEST RESOURCE CATEGORY

Primary: OAR / Other: Equipment and Personnel.

LOCATION

ESL Defence Ltd, 16 Compass Point, Ensign Way, Hamble, Southampton, Hampshire, UK.

NARRATIVE DESCRIPTION

The Trials/Test Support Group has extensive experience in operating long range Electro-Optical/Infrared (EO/IR) threat simulators to perform test and evaluation of Aircraft Survivability Equipment (ASE). This support is provided by Subject-Matter Experts to assist with the planning and operation of the threat emitters either those deployed on the open-range or leased as part of the support exercise.

The Trials/Test Support Group can also provide the service of data collection and data analysis and provide a Final Report from this data. One of the major contributors to the success of performing a test and evaluation exercise is to ensure that the probability of declaration from the various ASE sensors threat is high and if possible 100 percent. To achieve this high probability with today's high technology sensors requires a combination of representative missile signatures and operator experience in the understanding of the limitations of the threat emitter when fired at a moving target. The Trials/Test Support Group Engineers with their many years of international experience of stimulating many different types of missile warning system can provide the required expertise.

In addition, and perhaps of equal importance, is the performance of the EO/IR threat emitters. ESL has developed a comprehensive range of high fidelity long range threat emitters. These threat emitters include both UV and IR Emitters, known as Mallina and Phoenix, for the test and evaluation of UV and IR missile warners, laser warning receivers and for providing simulation of muzzle flash for the simulation of Hostile Fire Indicators. Further, by combining these threat emitters with additional EO/IR modules, including an IR Detector to measure the output from the DIRCM countermeasure, an end-to-end evaluation of a DIRCM system can be performed by what is known as the Mallina DIRCM Cluster. Further, the Trials/Test Support Group can provide a comprehensive set of flight line test sets that can test the aircraft just prior to the test and evaluation flight to ensure that the system under test is operating correctly.

UV LED Mallina

IR Phoenix

DIRCM Mallina Cluster

CAPABILITY SUMMARY

Trials/Test Support Activities
• The Trials Support Group comprises a number of subject-matter experts in simulation of missile and hostile fire for the simulation of aircraft survivability equipment. This support can be provided to operate either the open-range legacy equipment or ESL's comprehensive portfolio of threat emitters that can be provided on a lease basis. The support includes: • Pre-test and evaluation programme planning • Aircraft flight test path planning • Development of optimised missile profiles for use in the threat emitters • Operation of the threat emitters • Training of range operational staff • Trails data collection • Analysis of trials data • In addition to the above, ESL can provide flight line test equipment to test the System Under Test (SUT) to establish just prior to the test flight, on a "Go/No-Go" basis, that the SUT is functioning correctly. The flight line test equipment portfolio comprises: • Solent – to test omni directional IR Jammer • UV and IR Baringa – to test UV and IR missile warners respectively • Hydra – to test laser warning receivers • MEON to perform an end-to-end test of a DIRCM system • Multi-spectral test set – to test ASE equipment that requires simultaneous multi-spectral stimuli
Support Hardware and Software
• The EO/IR threat emitters simulators available for lease comprise: • UV and IR Griffen – to stimulate UV and IR missile signatures at ranges in excess of 5 km • UV LED Mallina – to simulate UV missile warners and UV hostile fire indicators (muzzle flash only) at ranges in excess of 8 km • Red and Blue HP Phoenix – to simulate IR missile warners and IR hostile fire indicators (muzzle flash only) at ranges in excess of 3 km • IRM-16 IR Beacon and Detector Module – to provide an IR beacon for the DIRCM fine tracking system to lock on to and measure the characteristics of the DIRCM countermeasure beam • Mallina Laser Range Finder Module – to provide a means to establish the range of the SUT and if selected auto-selection of the appropriate profile for that range • Tripod Legs and Head – to support the threat emitters. • Threat Emitter Management Software Tools – to download profiles into the threat emitter and remotely operate the threat emitters from a Desk-top PC or Laptop • Missile Signature Development Tools – to provide missile signatures based on public domain missile data

POINT OF CONTACT

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Annex B – MEASURES OF PERFORMANCE (MOPs)

B.1 INTRODUCTION

This Handbook focuses on EW Developmental Test & Evaluation (DT&E) and consequently MOPs are the central metrics. It is important, however to understand how MOPs fit into the overall hierarchy of test requirements, objectives, and associated measures. It is also important to understand what a measurement is and what information it conveys. Finally, this annex discusses some common MOPs. It is not intended to be definitive or an exhaustive compilation. It is intended to make the reader think about what details need to be addressed and documented in the planning stages to avoid disagreements later in the programme when they are much more difficult to resolve.

B.2 REQUIREMENTS, OBJECTIVES, AND MEASURES

Test requirements ultimately derive from operational needs identified by the military end user. These requirements are expressed as Critical Operational Issues (COI) and are defined as: "A key Operational Effectiveness (OE) and/or Operational Suitability (OS) issue (not a parameter, objective, or threshold) that must be examined in Operational Test and Evaluation (OT&E) to determine the system's capability to perform its mission. A COI is normally phrased as a question that must be answered in order to properly evaluate OE (e.g., "Will the system detect the threat in a combat environment at adequate range to allow successful engagement?") or OS (e.g., "Will the system be safe to operate in a combat environment?"). A COI may be decomposed into a set of Measures Of Effectiveness (MOE) and/or Measures Of Performance (MOP), and Measures of Suitability (MOS)." [1] Furthermore, the MOE, MOP, and MOS are defined as:

- **MOE**: Measure designed to correspond to accomplishment of mission objectives and achievement of desired results. MOEs may be further decomposed into Measures of Performance and Measures of Suitability. [2]
- **MOP**: Measure of a system's performance expressed as speed, payload, range, time on station, frequency, or other distinctly quantifiable performance features. Several MOPs and/or Measures of Suitability may be related to the achievement of a particular Measure Of Effectiveness (MOE). [3]
- **MOS**: Measure of an item's ability to be supported in its intended operational environment. MOSs typically relate to readiness or operational availability, and hence reliability, maintainability, and the item's support structure. [4]

MOPs are most commonly encountered as contractual specification requirements or other DT&E requirements. Some examples include: response times, Angle Of Arrival (AOA) measurement error, maximum detection range, etc.

B.3 MEASUREMENTS

One of the most important axioms in T&E is that system requirements must be testable. This means that the test must produce a meaningful answer to the questions asked. Whether or not a system meets its requirements will usually be determined by a measurement or series of measurements.

Measurement theory and statistics are complex fields and detailed treatments are beyond the scope of this Handbook. A measurement, by one definition, "in the broadest sense, is defined as the assignment of numerals to objects or events according to rules." [5] While there is controversy among statisticians regarding the four scales or classifications of measurement shown in Table B-1, they serve as a good starting point for a discussion of MOPs.

Table B-1: Measurement Scales [6].

Scale	Attributes	Permissible Statistics (Examples)	Common Examples
Nominal	Classification only.	Number of Cases, Mode	First Names
Ordinal	Rank ordered – the differences between the values are not meaningful.	Median, Percentile	Hardness of Minerals, Quality of Leather
Interval	Uses a scale with an arbitrary zero point (can have numbers less than zero) – differences between values are meaningful, but ratios of values are not meaningful, i.e., 60°F is not twice as "hot" as 30°F.	Mean, Standard Deviation, Correlation, Regression, Analysis of Variance	Fahrenheit or Celsius Temperature Scales
Ratio	Uses a scale with an non-arbitrary zero point (cannot have numbers less than zero) – ratios of values are meaningful, i.e., a weight of 20 lbs. is twice as much as 10 lbs.	All statistics permitted for interval scales plus the following: geometric mean, harmonic mean, coefficient of variation, logarithms	Rankin or Kelvin Temperature Scales

The individuals charged with generating specification requirements should consult with experienced testers and analysts. This ensures that types of measurements are appropriate to the task and that the required data can be collected in sufficient quantities and at sufficient rates. Proper consideration of the measurements and associated analysis techniques will not only help answer the question of whether or not a System Under Test (SUT) meets its specification requirements, but will also support a broader characterization of SUT performance.

Data analysts should strive to choose the measurement scale that retains the maximum amount of information. Information retention can be illustrated using bombing MOPs as an example. Consider a specification where a hit or miss is determined by a specified bomb miss distance (a nominal measurement). A significant amount of information is lost by just evaluating whether or not each bomb produces a hit or a miss. By focusing the analysis on vector miss distances (a ratio measurement); analysts can determine much about the system by analyzing the range and direction of the errors.

B.4 MOP CONSIDERATIONS

Test designers must consider MOPs in light of how a SUT functions. As an example, consider the objective of evaluating the performance of a Radar Warning Receiver (RWR). The evaluation needs to address several different MOPs. The specification requirements will be expressed as MOPs.

In a perfect world, the system contractual specification requirements document would define not only the specific MOPs to be evaluated but also:

- The specific conditions under which the data will be collected.
- The data reduction, analysis, evaluation process, including statistical treatments.

Failure to address these considerations can cause unexpected variability in the results and possibly incorrect measurements and inaccurate results. The simplified case shown Figure B-1 illustrates how this can occur. The dwell structure shown could have a significant effect on the ability of the RWR to detect and identify radar A. If radar A is operating between 9.0 and 10.0 GHz the RWR doesn't need to make any decisions when a signal is detected; the measured frequency and Pulse Repetition Interval (PRI) are sufficient to make a unique identification. If, however, radar A is operating at 8.5 GHz the Mission Data File (MDF) has two other radars with which to contend. Assume that Radar B is ambiguous in frequency and PRI with radar A then the RWR will need to do additional processing to resolve the ambiguity; perhaps by determining scan type or rate or by a more detailed pulse analysis.

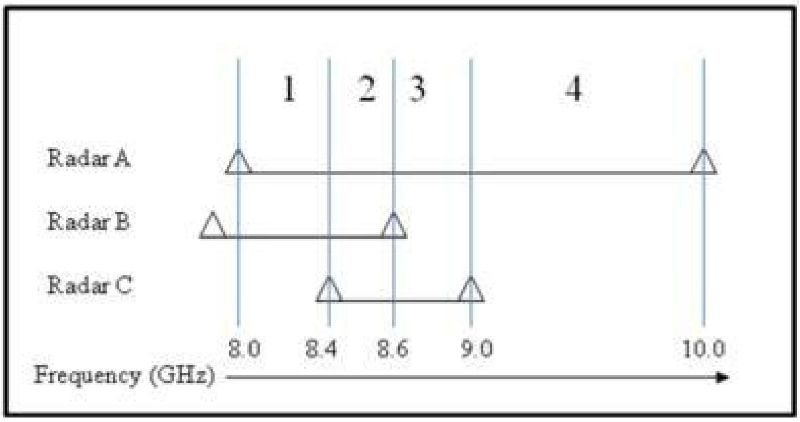


Figure B-1: Notional RWR Dwell Structure.

Therefore, it is likely that when radar A is operating at 8.5 GHz the response time will increase due to the additional possessing required to resolve the ambiguity with radar B and the likelihood of a misidentification also increases. If a test team elected to conduct a majority of the testing using radar A operating in frequency region 4, the RWR performance could be radically different than if it occurred in regions 1, 2, or 3. Test designers need to be aware of conditions such as this and consider them when designing test matrices.

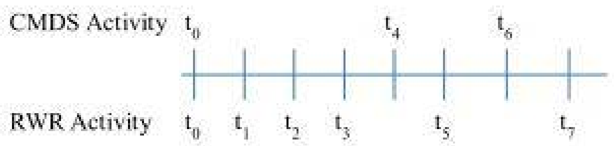
B.5 SELECTED MOPs

B.5.1 Receiver MOPs

This section addresses receiver MOPs by focusing on their applicability to RWRs, although they may also be applied to other receiver applications.

B.5.1.1 Response Time

Response time is one of the most important MOPs. It is a ratio measurement since there is an absolute zero reference. Generically, it is the elapsed time between two events. A federated or integrated EW suite may have several response times associated with its performance. Figure B-2 shows some of the response times associated with the simple case of a federated EW system with an RWR serving as the EW data bus controller and a mission computer serving as the avionics data bus controller. In this case, the two most important response times are, from a military utility viewpoint, the time between the illumination by a hostile radar and the time that the system warns the aircrew and the time of the CMDS dispense. However, from a T&E and systems engineering standpoint each of the intermediate time intervals are also critical.



t_0 - Time of initial valid illumination by a radar
t_1 - Time of initial detection
t_2 - Time of initial identification
t_3 - Time display message made available on the avionics data bus
t_4 - Time that threat information is made available to the CMDS via EW data bus
t_5 - Time mission computer commands display
t_6 - Time of CMDS dispense
t_7 - Time of display to aircrew

Figure B-2: Response Times.

Contractual system specification requirements should clearly identify the system response time budgets that support the overall mission requirements such as the time to display a warning to the aircrew or generate a CMDS dispense. The simple case described above could involve up to three separate contractors: the RWR manufacturer, the CMDS manufacturer, and the airframe integration contractor.

When there is a deficiency in the overall system performance it is important to be able to identify the specific deficiency and who is responsible. The RWR manufacturer only controls the sequence of events leading up to making a display message available on the avionics data bus. The time between the message availability and the mission computer processing it, sending it to the display generator, and generating the display is under the control of the avionics integration contractor. Similarly, the CMDS manufacturer only controls the activity subsequent to receiving data bus messages.

Note that the response time MOP does not necessarily require a correct identification. Although not ideal, if the RWR displays an incorrect symbol and generates an audible warning tone in a timely manner the aircrew still has an opportunity to react. It is better to have an incorrect symbol displayed rapidly than to display the correct symbol when it is too late. If a system incorrectly identifies a threat radar it will be penalized using other MOPs such as percent correct identification.

Response time data, as with other data, can be described by the central tendency and the spread of the data. They are rarely normally distributed and usually skewed to the right. Each individual response time must be greater than zero, while occasionally, the system will fail to generate a warning and the response time will be effectively infinite.

An average response time value must be treated carefully. First, consider using the mean. When a system fails to generate a warning, a mean cannot be calculated directly. One method of computing a mean when a data sample includes non-response is to transform the data.

Take a simple case with three samples: 2.0 second, 4.0 seconds, and no response. A mean value can be determined by transforming the data by taking the inverse of each value: 0.5, 0.25, and 0.0. The mean of the transformed data is 0.25. Transforming the data again produces a mean value of 4.0 seconds. Non-responses do not pose a problem for computing the median. In any case the test team must agree on the data analysis methods.

The skewed distribution poses a problem for evaluating the spread of the data. For this reason, RWR response time specifications are commonly expressed as percentiles, for example: 90% of the responses shall be less than X seconds. This method has the advantage of being easy to compute and gives some insight into both the central tendency and the spread of the data. Figure B-3 shows a hypothetical data set for a threat system with an acquisition radar, a target tracking radar, and a missile guidance radar; each with its own specification requirement. The box and whiskers plot is an effective way of presenting the data. In Figure B-3, if the response time specifications are 90% less than X seconds, then the RWR meets specifications for the missile guidance and acquisition radars, but does not meet specification for the target tracking radar.

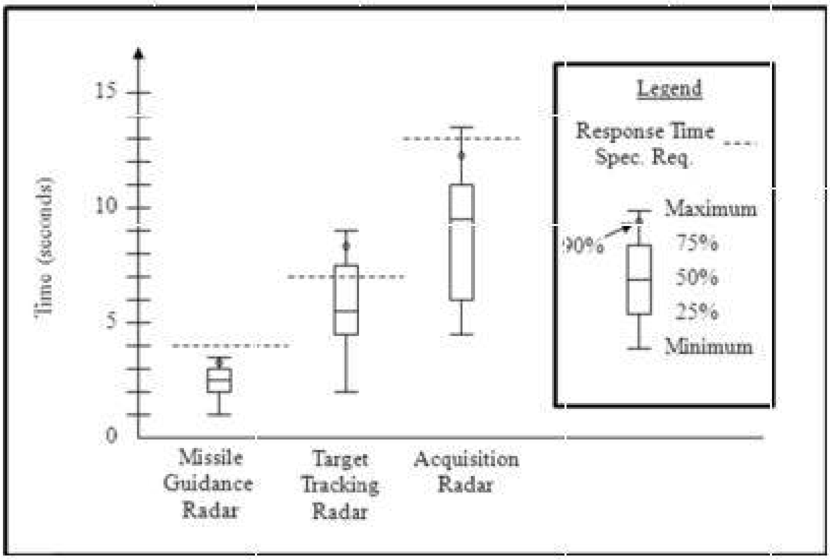


Figure B-3: Percentile Specification for a Hypothetical RWR (Not Real Data).

B.5.1.2 Correct Initial Identification Percentage

Radar directed threat systems are often composed of multiple beams. Each time an RWR is presented with a radar beam the system has an opportunity to correctly identify the beam. The correct identification percentage is simply the ratio of the number of correct identifications to the number of identification opportunities multiplied by 100.

B.5.1.3 Correct Beam Correlation Percentage

When multiple beams are present the RWR should internally identify each beam individually and correlate them such that only a single symbol associated with the most lethal operating condition of the threat radar is displayed. Anytime more than one beam is present the system has an opportunity to correctly correlate them or to not correlate them if they are from different radar systems. The correct correlation percentage is simply the ratio of the number of correct beam correlations to the number of correlation opportunities multiplied by 100.

B.5.1.4 Correct Mode Change Percentage

Some radars, such as airborne fire control radars, only have a single beam with which to perform multiple functions. A common engagement sequence of events would be for the radar to transition from a search mode, to target tracking mode, and ultimately to a missile launch mode. An RWR should detect each mode change by the radar and update its track files. Every time that a radar transitions modes there is an opportunity for the RWR to correctly detect and process the change. The correct mode change percentage is simply the ratio of the number of correct mode changes to the number of mode change opportunities multiplied by 100. Each mode transition also presents opportunities to collect response time and identification data.

B.5.1.5 Maximum Detection Range

Receivers are typically required to detect specific signals at a specified maximum detection ranges. The measure can be accomplished in flight but it is time consuming to collect enough data to support a statistically meaningful assessment. This is particularly true in the case when a scanning receiver is attempting to detect a scanning radar. Hence, maximum detection range is a measure best evaluated analytically. In reality, the maximum detection range will be described by a statistical distribution. The power density associated with a given signal at the maximum detection range can easily be calculated and compared with the installed sensitivity to determine if the signal will be detected at that range. The installed sensitivity of a receiver is the product of the receiver sensitivity, transmission line losses, amplifier gain (if present in the installation), and the antenna gain and can be easily calculated. The receiver sensitivity and amplifier gain can be measured in a laboratory, the RF transmission line losses can be measured on the aircraft, and the antenna gain patterns can be obtained.

B.5.1.6 Angle Of Arrival (AOA) Measurement Accuracy

EW receiver systems have widely varying AOA accuracy requirements and depend on the purpose of the system, although most specify angular fields of regard. RWRs typically specify a 360 degree azimuth field of regard and are bounded by elevation bands.

The AOA accuracy is determined by analyzing the AOA measurement errors, where AOA error is defined as the difference between the AOA calculated by the system and the true AOA. The error data are often presented by angular bins; commonly as a Root-Mean-Squared (RMS) error versus angular bins.

AOA data can be complicated to analyze. If each measurement is an independent sample the analysis is relatively straightforward. However, most EW systems don't present raw AOA measurements; they typically filter or smooth the data before it is presented or applied. When AOA data are filtered or smoothed, they are no longer independent and care must be taken when performing statistical analyses. Professional statisticians should be consulted when dealing with non-independent data.

B.5.1.7 Geolocation Accuracy

Some EW systems need to determine the location of ground-based emitters. These systems commonly measure the AOA to the emitter and based on successive measurements and triangulation algorithms produce an error ellipse that should contain the emitter's location as shown in Figure B-4. The speed with which a system can accurately locate an emitter is a function of geometry; it takes longer to locate an emitter off the nose of the aircraft than one off the beam due to the less rapid change in absolute bearing to the emitter.

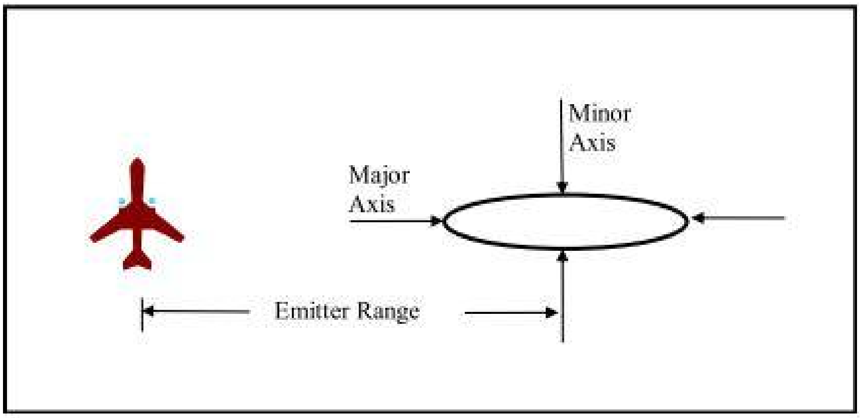


Figure B-4: Geolocation Error Ellipse.

Geolocation systems typically work in one of two ways. The first method is to track the calculated major and minor axes of the error ellipse until they collapse to a specified percentage of the estimated emitter range and when this occurs the system assigns the emitter a location at the centre of the error ellipse. The second method works the same way as the first method, but it does not stop computing the error ellipse and continues to update the computed position as long as the emitter is transmitting. The relevant difference from an analysis standpoint is that if the system determines a single location of an emitter, each location produces a discrete location error. While, if the system continuously computes emitter location the data will consist of a time-based series of emitter location errors.

One means of evaluating the performance of a system that continuously computes emitter location is a version of response time. The performance of the system is evaluated by determining the time for the major ellipse axis to collapse to a specified percentage of the range to the emitter; the time is a function of the geometry. Since there are many considerations consultation with a professional statistician is recommended.

B.5.2 Jammer MOPs

The ultimate measure of a jammer's utility is whether or not it can protect the aircraft it is designed to protect. This is exceedingly difficult to quantify, particularly in a flight test environment. Aircraft survivability presents a complex evaluation with many combinations and permutations, where jammer effectiveness is only one variable. Each engagement is unique and is a function of the specific conditions of the engagement. Other considerations include manoeuvres, tactics, and other countermeasures such as support jamming or chaff.

Some measures are relatively easy to quantify. Guided weapons or weapons direction systems must maintain an angular track on a target. Radar directed weapons also track targets in range and/or velocity. A means of evaluating the performance of a countermeasures system is to record the tracking error data associated with a target under non-jamming conditions, a condition known as dry and comparing them to the tracking error data collected under the same conditions with the countermeasures system operating, a condition known as wet. Another measure is to evaluate whether or not the jammer selected the correct technique.

While wet-to-dry track error comparisons are useful MOPs for analyzing EA technique effectiveness, they need to be used with caution, as different weapon systems have varying degrees of tolerance to track errors. Some systems can incur very large tracking errors and still successfully complete an engagement. Other MOPs that attempt to address more operationally relevant aspects of a jammer's performance are: cumulative missile miss distance comparisons, reduction in shot opportunities, and Reduction in Lethality (RiL). Each of these has strengths and weaknesses as well.

Simulated missile or projectile fly outs underlie a number of jammer MOPs. These simulations can be purely digitally modelled or use some combination of flight test generated radar data and modelled missile or projectile fly outs. EW data analysts need to fully understand the limitations of the models they use. One of the main EP features of modern radar systems is a well-trained operator in the loop. Understanding how the operator is represented in the model is vital to understanding its utility.

Historically, one of the major problems with using flight test data to support missile fly out modelling has been the inability to precisely and accurately know the location of the target aircraft. While OAR reference radars are good enough for many purposes, their accuracy imposed significant limitations on missile fly out simulations that attempted to determine hits or misses. The TSPI location errors for the test aircraft were often on the order of the warhead lethal radius, particularly for smaller missiles. This problem has been somewhat alleviated by the use of very accurate Global Positioning System (GPS) data as a Time-Space-Position Information (TSPI) source. Testers should remain aware of the importance of precise and accurate target TSPI data.

No single MOP comprehensively addresses the performance of an EA system; however, every good MOP indicates something about the performance of an EA system. A prudent analyst will examine as many MOPs as practical to evaluate the system performance.

B.5.2.1 Tracking Errors

Dry versus wet tracking errors are commonly presented in a range versus tracking error format; with the range separated into bins. Median errors are most commonly presented. Data are presented by threat system and test conditions and normally consist of a compilation of several individual passes. Figure B-5 shows an example of median range tracking error plot. Median is more commonly used than mean as an average since a small number of very large errors can cause misleadingly large errors if the mean is used.

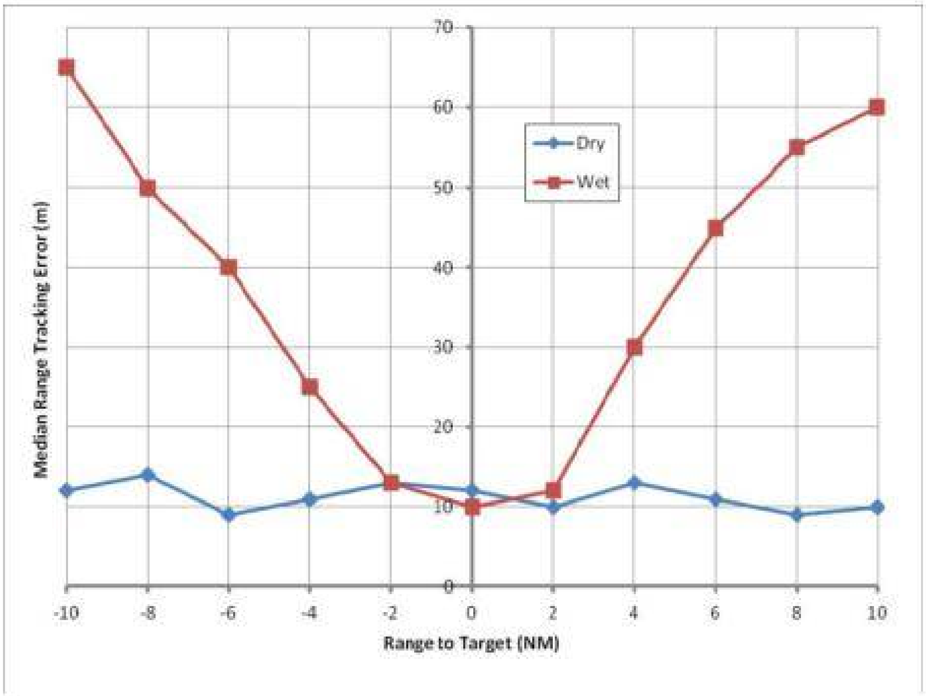


Figure B-5: Sample Median Range Tracking Error Plot (For a Given Threat Radar and Test Condition).

B.5.2.2 Cumulative Missile Miss Distances

Cumulative missile miss distance plots present the results of simulated missile fly outs as a comparison of dry versus wet results. Figure B-6 shows a sample graph. The graph indicates that jamming has increased the missile miss distance. Ninety percent of the dry run miss distances were within 10 meters while only 10 percent of the wet run miss distances were within 10 meters. The data should be collected to the maximum extent possible under the same conditions for both dry and wet runs.

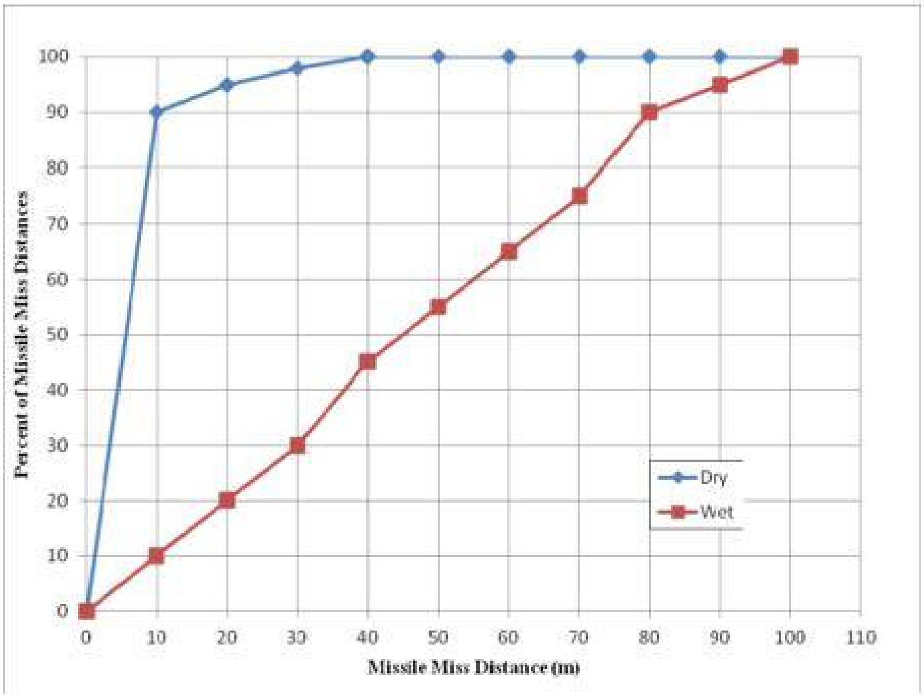


Figure B-6: Example of a Missile Miss Distance Cumulative Percentage Plot.

B.5.2.3 Reduction in Shot Opportunities

One of the benefits of effective self protection jamming is that the EA technique will disrupt the threat system and deny the threat system operators shot opportunities. Reduction in Shot Opportunities (RiS) can be expressed as:

$$RiS = \left[1 - \frac{\frac{Number\ of\ Shots\ (Wet)}{Number\ of\ Passes\ (Wet)}}{\frac{Number\ of\ Shots\ (Dry)}{Number\ of\ Passes\ (Dry)}}\right] \times 100$$

B.5.2.4 Reduction in Lethality

Reduction in Lethality (RiL) is a measure that attempts to quantify the effectiveness of the jammer. It is defined as follows:

$$RiL = \left[1 - \frac{\frac{Number\ of\ Hits\ (Wet)}{Number\ of\ Passes\ (Wet)}}{\frac{Number\ of\ Hits\ (Dry)}{Number\ of\ Passes\ (Dry)}}\right] \times 100$$

RiL has two main advantages: it is easy to compute and it focuses on whether or not the threat system successfully engaged the protected aircraft. However, it has a number of disadvantages. The primary shortfall comes from determining the definition of a "hit". Hits are commonly determined by comparing the calculated or simulated missile miss distance to a predetermined miss distance from the aircraft. This distance is often based on the largest dimension of the aircraft (for example, half of the wing span) plus some fixed number representing the lethal radius of the warhead. This considerably oversimplifies the warhead-target interaction, particularly for missiles with small warheads. Another shortfall is that the term RiL is a misnomer; the expression defined above might more properly be termed a Reduction in Susceptibility, since it address hits and misses instead of kills or lethality. Additionally, when RiL is based on flight test data the previously discussed problem of target location accuracy and precision must be considered.

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[2] DAU, p. B-103.

[3] DAU, p. B-103.

[4] DAU, p. B-103.

[5] Stevens, S.S., "On the Theory of Scales of Measurement", Science, Vol. 103, No. 2684, 7 June 1946, p. 677.

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Annex C – JAMMING-TO-SIGNAL RATIO

C.1 INTRODUCTION

J/S is one the most important measures in EA technique design and performance analysis. It is defined as the ratio of the jamming signal strength J within the victim receiver's bandwidth to the desired signal strength S. To be effective, a jamming technique must insert sufficient jamming energy into the receiver's pass band to produce a desired effect on the victim system. There are a number of different applications and EA techniques and the required J/S varies widely. Some techniques may be effective with less than 0 dB (1:1) while others may require 30 dB (1000:1) or more.

This annex shows the development of the J/S expression for two of the most common forms: defensive EA (SPJ) against a ground-based radar and offensive EA (SOJ) against a ground-based radar. Other cases such as defensive EA against a semi-active missile and communication jamming can be developed in a similar manner and are left to the reader.

C.2 J/S FOR DEFENSIVE EA AGAINST A GROUND-BASED RADAR

Figure C-1 illustrates the defensive EA case. A ground-based radar is tracking a target aircraft carrying a defensive EA system and the defensive EA system is jamming it. The main beam of the EA system is pointing toward the victim radar.

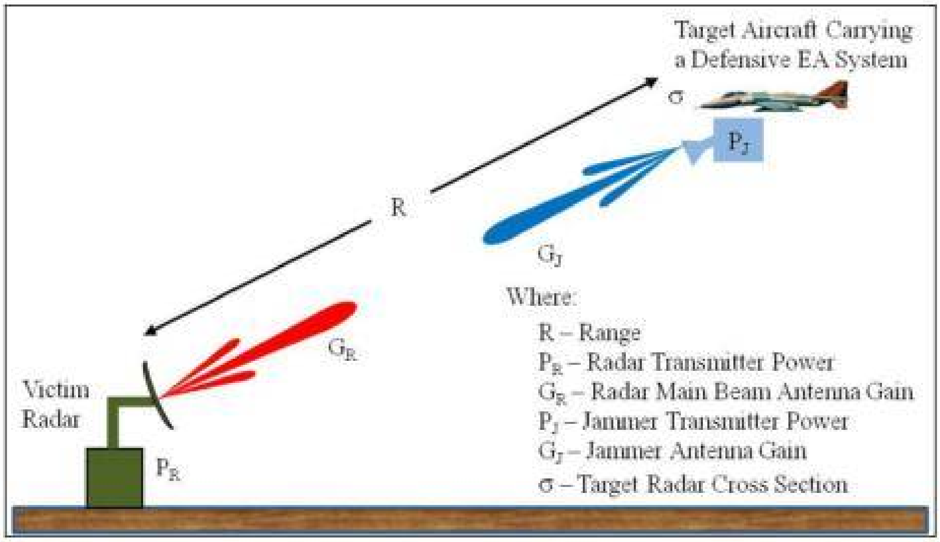

Figure C-1: J/S for Defensive EA Against a Ground-Based Radar.

The first step is to determine the signal power S returned from the target at the victim radar receiver.

If the power generated by the radar transmitter P_R is distributed isotropically (uniformly in all directions as over the surface area of a sphere) the power density, in Watts per unit area, at a given range R can be determined by the equation:

$$Power\ density\ from\ an\ isotropic\ antenna = \frac{P_R}{4\pi R^2} \tag{C1}$$

Radars, however, employ directive antennas to focus the transmitted energy in a desired direction, thereby multiplying the isotropic power density by the gain G_R of the radar antenna; therefore:

$$Power\ density\ from\ an\ directive\ antenna = \frac{P_R G_R}{4\pi R^2} \tag{C2}$$

A certain portion of that energy intercepting the target at range R is backscattered toward the radar. The amount of backscattered energy is related to the Radar Cross-Section (RCS) σ of the target. The RCS has units of area and is a function of the electrical properties of the target. The incident energy returning from the target to the radar also incurs a $1/4\pi R^2$ spreading loss. Therefore:

$$Power\ density\ of\ the\ returning\ signal\ \ at\ the\ radar = \frac{P_R G_R}{4\pi R^2}\,\frac{\sigma}{4\pi R^2} \tag{C3}$$

The radar antenna will capture a portion of returning signal. The amount of energy captured by the antenna is determined by its effective aperture A_e. The effective aperture, as with the RCS, has units of area and is also a function of the electrical properties of the antenna. The desired signal power S returned from the target is:

$$S = \frac{P_R G_R}{4\pi R^2}\,\frac{\sigma}{4\pi R^2}\,A_e = \left[\frac{P_R G_R\,\sigma A_e}{(4\pi)^2 R^4}\right] \tag{C4}$$

The relevant characteristic of this expression in the J/S discussion is that the desired signal power S at the radar varies as a function of R^{-4}.

The jammer power J at the victim radar can be derived in a similar manner using the jammer's transmitter power P_J and the jammer's antenna gain G_J. The power density transmitted by the jammer is:

$$Power\ density\ from\ a\ directive\ jammer\ antenna = \frac{P_J G_J}{4\pi R^2} \tag{C5}$$

The jammer energy entering the radar antenna will encounter the same effective aperture as the radar signal. Therefore, the jamming power produced at the radar antenna output is:

$$J = \frac{P_J G_J}{4\pi R^2}\,A_e \tag{C6}$$

Note that, unlike the expression for the desired radar signal S, which varies as a function of R^{-4}, the expression for jammer power at the victim radar varies as a function of R^{-2}. This is because the radar signal is a two-way path while the jammer transmission is only a one-way path.

J/S can then be described as:

$$J/S = \frac{P_R G_R\,4\pi}{P_J G_J\,\sigma}\,R^2 \tag{C7}$$

The R^2 term dominates the equation and the somewhat counterintuitive effect is that J/S decreases exponentially as the jammer gets closer to the radar it is jamming. The extreme result is that when the range approaches zero, J/S also approaches zero.

Figure C-2 illustrates an example of how the jamming and signal powers vary as functions of range. Note that both signals are increasing in power as the range to the target decreases, but the target return signal is increasing at a faster rate, eventually equalling it and overtaking it. [1]

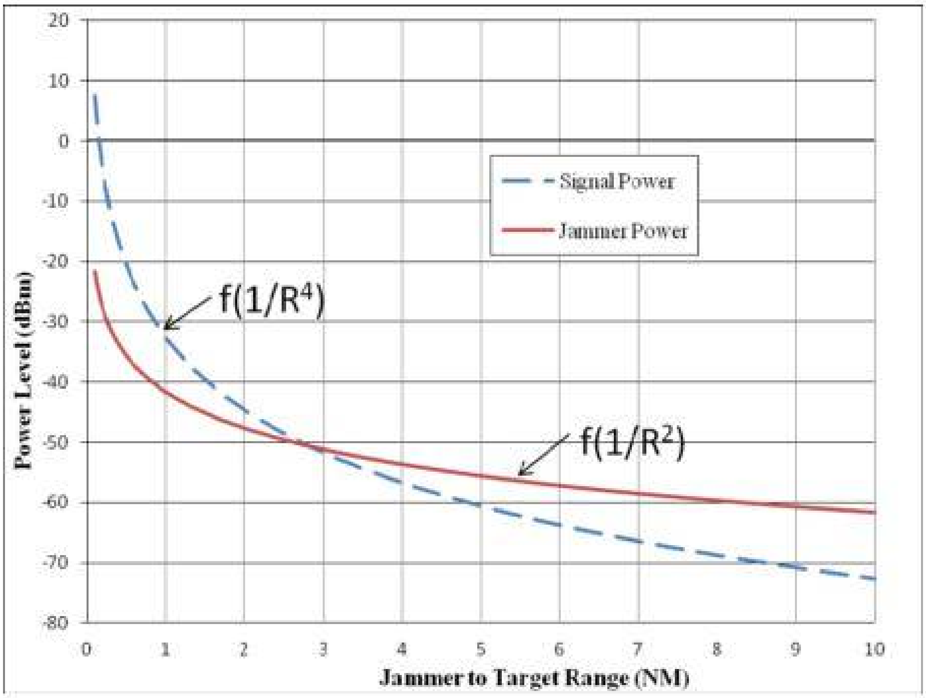

Figure C-2: Jamming and Target Return Signal Power Variation.

Figure C-3 shows the same data presented in terms of J/S. A hypothetical EA technique requires a minimum J/S of 4:1 (6 dB) to be effective. The J/S falls below 4 at approximately 5.7 Nautical Miles (NM). This range is often called the burnthrough range, i.e. the range at which the EA system no longer has enough of a power margin over the target signal return to be effective. In practice it is difficult to identify a specific burnthrough range as factors such as radar operator skill and target RCS variation can affect the ability of the radar system to engage a target.

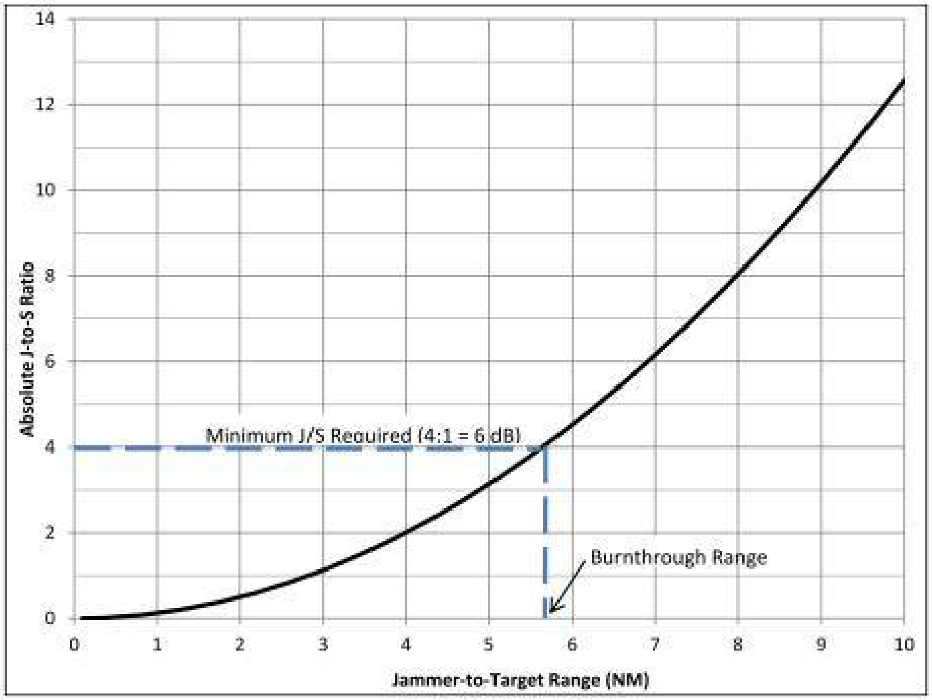

Figure C-3: J/S and Burnthrough Range.

C.3 J/S FOR OFFENSIVE EA AGAINST A GROUND-BASED RADAR

The J/S computation is different for the offensive EA case. The geometry is illustrated in Figure C-4. The stand-off jamming is performed by a support EA aircraft with the intent of protecting other aircraft. The radar signal return power S is calculated the same way as in the defensive EA case; however, the J calculation will be different since the aircraft carrying the jammer may be offset in angle from the protected aircraft and will be operating at a different range (R_J).

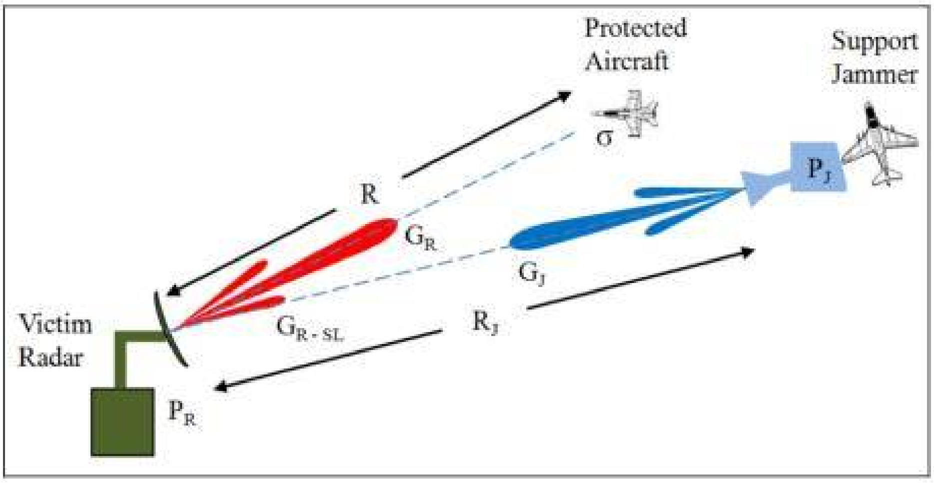

Figure C-4: J/S for Offensive EA Against a Ground-Based Radar.

Offensive EA is frequently directed against azimuth-scanning surveillance radars. Often the support jamming aircraft will be operating at a different azimuth than the protected aircraft. This means that when the protected aircraft is in the main beam of the surveillance radar, the jamming energy from the support jammer is entering the radar through a sidelobe with a different gain G_{R-SL} than the radar antenna main lobe G_R. This also means that unlike in the defensive EA scenario shown in Figure C-4, the effective aperture will be different (A_e'). In practice, as the antenna rotates, the jammer will jam over the entire radar antenna pattern.

For the scenario shown, jammer power density at the victim radar is:

$$J = \frac{P_J G_J}{4\pi {R_J}^2} A_e' \tag{C8}$$

The resultant expression for J/S is:

$$J/S = \frac{P_J G_J}{P_R G_R} \frac{R^4}{R_J^2} \frac{4\pi}{\sigma} \frac{A_e'}{A_e} \tag{C9}$$

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Annex D – GLOSSARY

Airborne Testbeds – Ranging from small aircraft with pod-mounted components or systems to large aircraft designed for spread-bench installation and testing of EW and avionic systems. They permit the flight testing of EW components, sub-systems, systems, or functions of avionic suites in early development and modification, often before the availability of prototype or production hardware.

Amplitude Modulation (AM) – Modulation of the amplitude of a radio carrier wave in accordance with the strength of the audio or other signal. A radar angle tracking method using the time varying amplitude of the returning target signal to generate an error signal to correct the boresight position of the antenna.

Angle Of Arrival (AOA) – The direction of arrival of a signal normally referenced to the aircraft body coordinate system.

Antenna Gain – The dimensionless ratio of the intensity of an antenna in a given direction to the intensity that would be produced by a hypothetical ideal antenna that radiates equally in all directions (isotropically) and has no losses.

Anti-Radiation Missile (ARM) – An air-to-surface missile with an RF seeker designed to track and home on threat radar transmission.

Aperture – An EM opening through which energy can pass.

Beamwidth (half-power) – In a plane containing the direction of the maximum of a beam, the angle between the two directions in which the radiation intensity is one-half the maximum intensity of the beam.

Blanker – A device that manages RF suppression management in a platform. Also called a Central Suppression Unit.

Burn-through Range – The range at which a jamming technique is no longer effective. The point where the target skin return energy exceeds the jamming energy by a sufficiently large margin to negate the EA technique's effectiveness.

Chaff – A form of EA in which aircraft or other targets spread a cloud of small, thin pieces of aluminium, metallised glass fibre or plastic, which either appears as a cluster of secondary targets on radar screens or swamps the screen with multiple returns.

Closed-Loop – A system in which the output has an effect on the input quality in such a manner as to maintain the desired output.

Communications Intelligence (COMINT) – Technical information and intelligence derived from foreign communications by other than the intended recipients.

Continuous Wave (CW) – An EM transmission that is continuously operating, as opposed to pulsed operation.

Countermeasures – That form of military science that, by the employment of devices and/or techniques, has as its objective the impairment of the operational effectiveness of enemy activity.

Countermeasures Dispensing System (CMDS) – A system that dispenses expendable countermeasures, such as chaff and flares.

Data Analysis Plan (DAP) – A document that details how the collected test data will be reduced, processed, analysed, and used to calculate the MOPs.

Data Reduction – The process of converting recorded data to engineering units and the data analysis process to produce a data set that can be evaluated.

Deceptive Jamming – An EA technique focused on deceiving an operator or the automatic detection and processing functions of a radar; also called false target jamming.

Digital RF Memory (DRFM) – Technology employed in RF countermeasures systems. DRFM-based techniques allow a jammer to produce very high quality false targets. They do this by sampling the incoming pulses and storing them. The stored pulses retain the nuances of the received pulses, such as phase coherency or intrapulse modulation. These stored pulses can them be modulated and retransmitted back toward the victim radar.

Directed Energy (DE) – An umbrella term covering technologies that produce a beam of concentrated EM energy or atomic or sub-atomic particles. A DE weapon is a system using DE primarily as a direct means to damage or destroy adversary equipment, facilities, and personnel. DE warfare is military action involving the use of DE weapons, devices, and countermeasures to either cause direct damage or destruction of adversary equipment, facilities, and personnel, or to determine, exploit, reduce, or prevent hostile use of the EM spectrum through damage, destruction, and disruption.

Dry – A test condition where the EA system is not operating, i.e., in standby mode or off.

Developmental Test & Evaluation (DT&E) – 1. Any testing used to assist in the development and maturation of products, product elements, or manufacturing or support processes. 2. Any engineering-type test used to verify status of technical progress, verify that design risks are minimised, substantiate achievement of contract technical performance, and certify readiness for initial Operational Testing (OT). Development tests generally require instrumentation and measurements and are accomplished by engineers, technicians, or soldier operator-maintainer test personnel in a controlled environment to facilitate failure analysis.

Dynamic Range – The input signal amplitude range that the receiver can process properly. The lower limit is the receiver sensitivity (MDS is commonly used). There is no universally accepted definition for the lower or the upper limit of the input signal level.

Effective Radiated Power (ERP) – The power transmitted by a system; the product of the transmitter power, transmission line losses, and antenna gain.

Effectiveness – The extent to which the goals of the system are attained, or the degree to which a system can be elected to achieve a set of specific mission requirements. Also, an output of a cost-effectiveness analysis.

Electromagnetic Wave – One of the waves that are propagated by simultaneous periodic variations of the electric and magnetic field intensity and that include radio waves, infrared, visible light, ultraviolet, X rays, and gamma radiation.

Electromagnetic Compatibility (EMC) – The ability of systems, equipment, and devices that utilise the EM spectrum to operate in their intended operational environments without suffering unacceptable degradation or causing unintentional degradation because of EM radiation or response. It involves the application of sound EM spectrum management; system, equipment, and device design configuration that ensures interference-free operation; and clear concepts and doctrines that maximise operational effectiveness.

Electromagnetic Hardening – Action taken to protect personnel, facilities, and/or equipment by filtering, attenuating, grounding, bonding, and/or shielding against undesirable effects of EM energy.

Electromagnetic Interference (EMI) – Any EM disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics and electrical equipment. It can be induced intentionally, as in some forms of electronic warfare, or unintentionally, as a result of spurious emissions and responses, intermodulation products, and the like.

Electromagnetic Pulse (EMP) – The EM radiation from a strong electronic pulse, most commonly caused by a nuclear explosion that may couple with electrical or electronic systems to produce damaging current and voltage surges.

Electromagnetic Spectrum – The range of frequencies of EM radiation from zero to infinity. It is divided into 26 alphabetically designated bands.

Electronic Attack (EA) – The use of EM energy, Directed Energy (DE), or anti-radiation weapons to attack personnel, facilities, or equipment with the intent of degrading, neutralising or destroying enemy combat capability and is considered a form of fires.

Electronic Protection (EP) – Actions taken to protect personnel, facilities, and equipment from any effects of friendly or enemy use of EM spectrum that degrade, neutralise, or destroy friendly combat capability.

Electronic Warfare (EW) – The use of EM or directed energy (DE) to control the EM spectrum or to attack the enemy.

Electronic Warfare Support (ES) – Actions taken by, or under direct control, of an operational commander to search for, intercept, identify and locate, or localise sources of intentional and unintentional radiated EM energy for the purpose of immediate threat recognition, targeting, planning, and conduct of future operations.

Electro-Optical (EO) – Of or relating to a branch of technology involving components, devices and systems which operate by modification of the optical properties of a material by an electric field.

Electronic Intelligence (ELINT) – Technical and geolocation intelligence derived from foreign non-communications EM radiations emanating from other than nuclear detonations or radioactive sources.

Emission Control (EMCON) –The selective and controlled use of EM, acoustic, or other emitters to optimise command and control capabilities while minimising, for operations security: a. detection, by enemy sensors; b. mutual interference among friendly systems; and/or c. enemy interference with the ability to execute a military deception plan.

Escort Jamming – A form of support jamming where the jamming aircraft flies along with the aircraft it is protecting.

False Alarm – A warning generated when no threat is present.

False Alarm Rate – The rate at which false alarms occur, normally expressed in false alarms per hour.

Flares – Expendable pyrotechnic defensive EA devices designed to capture the seeker of an IR-guided missile and seduce it away from the targeted aircraft.

Frequency Selectivity – A measure of the ability of a receiver to distinguish between two signals of different frequencies.

Geolocation – The process of determining the position of a ground-based emitter.

Hardware In The Loop (HITL) – Indoor test facilities that provide a secure environment to test EW techniques and hardware against simulators of threat systems. Primary EW HITL facilities contain simulations of hostile weapon system hardware or the actual hostile weapon system hardware. They are used to determine threat system susceptibility and to evaluate the performance of EW systems and techniques.

High-Energy Laser (HEL) Weapon – A system that directs light energy at targets using the properties of coherent EM radiation. HEL systems are often categorised by the method of excitation, cooling, or the gain material. Some HELs are gas-dynamic lasers. These lasers are pumped by combustion or an energetic chemical reaction. Some lasers have a liquid gain medium or are liquid-cooled. SSLs have a crystalline or glass gain medium. SSLs have recently become viable contenders for HEL applications. All lasers can be formed into a tight beam because of the property of coherence, meaning that the phase relationship is preserved to the point that interference of the waves can occur.

High-Power Microwave (HPM) – HPM weapons are systems that emit RF energy at high peak power levels and are often categorised by the bandwidth-to-frequency ratio of their waveforms. These are typically very large ratios. They have been divided into narrowband, wideband, and ultra wideband. HPM devices have a smaller effective range than the EMP effects of a nuclear weapon. Narrowband devices tend to operate on specific electronic vulnerabilities in the target and therefore, require knowledge of enemy systems to be effective. Ultra-wideband devices tend to be simpler and cheaper, using powerful transient waveforms, and requiring less knowledge of the target. A few HPM weapons function by making use of psycho-sensory or neural phenomena, rather than just high power levels, to deter human actions or cause confusion among attacking troops.

Infrared (IR) – EM radiation with a wavelength between 0.7 and 300 micrometres.

Infrared Countermeasures (IRCM) – EA techniques directed against IR-guided weapons.

Installed Receiver Sensitivity – A measure of how the receiver transmission line including the antenna and amplifiers (if present) affects the receiver system's MDS. If the transmission line has positive gain, the system sensitivity will increase and if it has negative gain it will decrease.

Installed System Test Facility (ISTF) – Facilities that provide a secure capability to evaluate EW systems that are installed on, or integrated with, host platforms. These test facilities consist of anechoic chambers in which free-space radiation measurements are made during the simultaneous operation of EW systems and host platform avionics and munitions.

Isolation – The amount of signal loss between a transmitting antenna and a receiving antenna. Sufficient isolation between antennas prevents EMI.

Intermediate Level (I-Level) Maintenance – That level of maintenance/repair of items that do not have to go to depot level for major work and are incapable of maintenance/repair at the organizational level.

Jamming-to-Signal (J/S) – The ratio of the jamming signal strength J within the victim receiver's bandwidth to the desired signal strength S. To be effective, a jamming technique must insert sufficient jamming energy into the receiver's pass band to produce a desired effect on the victim system.

Kinematics – The study of the geometry of motion; relates displacement, velocity, acceleration and time, without reference to the cause of the motion.

Laser Warning System (LWS) – An ES system designed to detect the laser energy associated laser range finders or beam riding missiles and warn the aircrew.

Line Replaceable Unit (LRU) – An essential support item removed and replaced at field level to restore an end item to an operationally ready condition. (Also called Weapon Replacement Assembly (WRA) and Module Replaceable Unit.)

Low Observable (LO) – LO platforms are characterised by reduced signatures, most prevalently in the RCS and IR realms.

Man Portable Air Defence System (MANPADS) – Short-range normally infrared guided (heat-seeking) SAMs.

Measure Of Effectiveness (MOE) – Measure designed to correspond to accomplishment of mission objectives and achievement of desired results. MOEs may be further decomposed into Measures of Performance and Measures of Suitability.

Measure Of Performance (MOP) – Measure of a system's performance expressed as speed, payload, range, time on station, frequency, or other distinctly quantifiable performance features. Several MOPs and/or Measures of Suitability may be related to the achievement of a particular Measure of Effectiveness (MOE).

Measurement Facilities (MF) – Facilities that establish the character of an EW related system/sub-system or technology. They provide capabilities to explore and evaluate advanced technologies such as those involved with various sensors and multi-spectral signature reduction.

Military End User – The military organisation using the weapons systems in combat.

Minimum Discernable Signal (MDS) – The lowest power signal that can be discerned from the noise, i.e., the point where the signal power is equal to the noise power in the receiver.

Missile Warning System (MWS) – An ES system that warns aircrew of attacks by passive homing missiles (most commonly IR-guided) by detecting the IR and/or UV signature of a missile rocket motor plume.

Mission – The objective or task, together with the purpose, which clearly indicates the action to be taken.

Mission Data – The compilation of threat system parametric data, such as frequency ranges, PRI, scan rates, scan types, etc., along with threat system identifications and priority. Mission data sets are normally tailored to meet the requirements for a specific theatre of operations.

Mission Data File (MDF) – The file containing the mission data sets that is loaded into an EA or ES system; analogous to computer application.

Model – A representation of an actual or conceptual system that involves mathematics, logical expressions, or computer simulations that can be used to predict how the system might perform or survive under various conditions or in a range of hostile environments.

Modelling and Simulation (M&S) – Used to represent systems, host platforms, other friendly players, the combat environment, and threat systems. They can be used to help design and define EW systems and testing with threat simulations and missile fly-out models. Due to the relatively low cost of exercising these models, this type of activity can be run many times to check 'what ifs' and explore the widest possible range of system parameters without concern for flight safety. These models may run interactively in real or simulated time and space domains, along with other factors of a combat environment, to support the entire T&E process.

Noise Jamming – An EA technique designed to prevent target detection by raising the noise level in a victim receiver to the point that the jamming energy exceeds the target energy.

Open Air Range (OAR) – Test facilities used to evaluate EW systems in background, clutter, noise and dynamic environments. Typically these resources are divided into sub-categories of test ranges and airborne testbeds. Open Air Range EW flight test ranges are instrumented and populated with high-fidelity manned or unmanned threat simulators. Additional emitter-only threat simulators are also used to provide the high signal density characterising typical operational EW environments.

Open-Loop – A system in which the output has no effect on the input signal.

Operational Flight Program (OFP) – The software performing the executive functions of a system; analogous to a computer's operating system.

Operational Security (OPSEC) – Protection of military operations and activities resulting from identification and subsequent elimination or control of indicators susceptible to hostile operations.

Operational Test & Evaluation (OT&E) – The field test, under realistic conditions, of any item (or key component) of weapons, equipment, or munitions for the purpose of determining the effectiveness and suitability of the weapons, equipment, or munitions for use in combat by typical military users; and the evaluation of the results of such tests.

Probability of Kill (P_K) – The product of susceptibility and vulnerability.

Program Introduction Document (PID) – A document provided by a test customer to a test facility identifying technical and schedule requirements. See Statement of Capability (SOC).

Pulse Width (PW) – The duration in time of an EM pulse.

Pulse Repetition Frequency (PRF) – The number of pulses per second.

Pulse Repetition Interval (PRI) – The time duration between the beginning of successive pulses.

Pulse-Doppler Radar – A type of radar that uses a high PRF coherent waveform to detect and track targets in the frequency domain. The technique also permits look-down, shoot-down operations by airborne radars.

Radar Cross-Section (RCS) – Is a measure of how detectable a target is by a radar. A larger RCS indicates that an object is more easily detected.

Radar Warning Receiver (RWR) – A system that detects, identifies, locates, and determines the relative lethality of radar directed threat systems. It serves to warn aircrew of hostile radar activity and provides cuing information to other countermeasures systems such as chaff dispensers.

Radio Frequency (RF) – Is a rate of oscillation in the range of about 30 kHz to 300 GHz, which corresponds to the frequency of electrical signals normally used to produce and detect radio waves.

Regression Testing – Testing conducted following a hardware, software, or mission data change to determine if the changes have inadvertently affected other aspects of system performance.

Role – A function or part performed in a particular operation or process.

Rules Of Engagement (ROE) – Describe how the ground-based and airborne threat simulators will operate during the test mission. ROE detail what restrictions the test requirements place on the threat simulator operators, particularly addressing target acquisition and reacquisition procedures and the use of EP features.

Scenario – A specific description of the many parameters characterising an encounter between one or more aircraft and a hostile air defence system or elements of that system.

Self-Protection Jammer (SPJ) – An EA system that protects the host platform.

Sidelobes – The lobes of the far field antenna radiation pattern that are not the main beam.

Signals Intelligence (SIGINT) – A category of intelligence comprising either individually or in combination all communications intelligence, electronic intelligence, and foreign instrumentation signals intelligence, however transmitted or intelligence derived from communications, electronic, and foreign instrumentation signals.

Simulation – A simulation is a method for implementing a model. It is the process of conducting experiments with a model for the purpose of understanding the behaviour of the system modelled under selected conditions or of evaluating various strategies for the operation of the system within the limits imposed by developmental or operational criteria. Simulation may include the use of analogue or digital devices, laboratory models, or "testbed" sites. Simulations are usually programmed for solution on a computer; however, in the broadest sense, military exercises, and wargames are also simulations.

Simulator – A system that can represent relevant characteristics of an actual threat system.

Spectral – Of or relating to the EM frequency characteristics of a signal.

Stand-In Jamming – A form of support jamming normally performed by Unmanned Aerospace Vehicles (UAV) operating within the engagement range of hostile air defence systems.

Stand-Off Jamming (SOJ) – A form of support jamming normally performed by manned aircraft operating outside the engagement range of hostile air defence systems.

Statement Of Capability (SOC) – A test facility's response to a customer's PID, documenting the cost, availability, and technical considerations or limitations.

Stimulator – A low fidelity piece of test equipment that can induce a desired response in a SUT without necessarily simulating the behaviour of an actual threat system.

Suitability – The degree to which a system can be placed and sustained satisfactorily in field use with consideration being given to availability, compatibility, transportability, interoperability, reliability, wartime usage rates, maintainability, safety, human factors, habitability, manpower, logistics supportability, natural environmental effects and impacts, documentation, and training requirements.

Support Jamming – Jamming conducted by one platform to protect another.

Susceptibility – The probability that an aircraft will be hit by a damage causing mechanism.

Synthetic Environment – Internetted simulations that represent activities at a high level of realism from simulations of theaters of war to factories and manufacturing processes. These environments may be created within a single computer or a vast distributed network connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioural models. They allow visualization of and immersion into the environment being simulated.

System Integration Laboratories (SIL) – Facilities designed to test the performance and compatibility of components, sub-systems and systems when they are integrated with other systems or functions. They are used to evaluate individual hardware and software interactions and, at times, involve the entire weapon system avionics suite. A variety of computer simulations and test equipment are used to generate scenarios and environments to test for functional performance, reliability, and safety. SILs are generally weapon system specific and are found in both contractor and Government facilities.

System Under Test (SUT) – The test article. This can be a component, equipment, sub-system, system or whole platform with installed systems.

Technology Readiness Level (TRL) – One level on a scale of one to nine, e.g., "TRL 3," signifying technology readiness pioneered by the National Aeronautics and Space Administration (NASA), adapted by the Air Force Research Laboratory (AFRL), and adopted by the Department of Defense as a method of estimating technology maturity during the acquisition process. The lower the level of the technology at the time it is included in a product development program, the higher the risk that it will cause problems in subsequent product development.

TEMPEST – Originally a codeword (hence capitalisation), since declassified. It is not an acronym. It refers to investigations and studies of compromising emissions. These are defined as unintentional intelligence-bearing signals which, if intercepted and analyzed, may disclose the information transmitted, received, handled, or otherwise processed by any information-processing equipment. NATO requirements defined in SDIP-27.

Temporal – Of or relating to the time domain.

Test and Evaluation (T&E) – Process by which a system or components are exercised and results analysed to provide performance related information. The information has many uses including risk identification and risk mitigation and empirical data to validate models and simulations. T&E enables an assessment of the attainment of technical performance, specifications, and system maturity to determine whether systems are operationally effective, suitable and survivable for intended use, and/or lethal.

Test Conductor – The individual responsible for the test point-by-test point execution of a test mission.

Test Director – The individual with overall responsibility for executing a test mission.

Time, Space, Position Information (TSPI) – Location data referenced to a coordinate system as a function of time.

Towed Decoy – A defensive EA system towed behind the host aircraft with the intent of providing a more seductive target to a threat system and one that creates an angle tracking error in the threat sensor system.

Type I Error – Rejecting null hypothesis when it is true.

Type II Error – Failing to reject a null hypothesis when it is false.

Ultraviolet (UV) – EM radiation with a wavelength shorter than that of visible light, but longer than X-rays, in the range 10 nm to 400 nm.

Unmanned Aerospace Vehicles (UAV) – An aerospace vehicle that is either remotely piloted or operates autonomously.

Unmanned Aerospace Systems (UAS) – UAS, which also means Unmanned Autonomous Systems, include UAVs and UCAVs (Unmanned Combat Air Vehicles).

Vulnerability – The conditional probability that an aircraft will be killed when struck by a damage causing mechanism.

Wet – A test condition where an EA SUT is operating in a transmitting mode.

Wild Weasel – An aircraft equipped with specialised receivers designed to detect, identify, and locate the source of hostile radar transmissions and ARMs to engage them.

Annex E – AGARD and RTO Flight Test Instrumentation and Flight Test Techniques Series

1. Volumes in the AGARD and RTO Flight Test Instrumentation Series, AGARDograph 160

Volume Number	Title	Publication Date
1.	Basic Principles of Flight Test Instrumentation Engineering (Issue 2) Issue 1: Edited by A. Pool and D. Bosman Issue 2: Edited by R. Borek and A. Pool	 1974 1994
2.	In-Flight Temperature Measurements by F. Trenkle and M. Reinhardt	1973
3.	The Measurements of Fuel Flow by J.T. France	1972
4.	The Measurements of Engine Rotation Speed by M. Vedrunes	1973
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22.	Application of Fiber Optic Instrumentation by L. Richards, A.R. Parker Jr., W.L. Ko, A. Piazza and P. Chan	2012

2. Volumes in the AGARD and RTO Flight Test Techniques Series

Volume Number	Title	Publication Date
AG237	Guide to In-Flight Thrust Measurement of Turbojets and Fan Engines by the MIDAP Study Group (UK)	1979

The remaining volumes are published as a sequence of Volume Numbers of AGARDograph 300.

Volume Number	Title	Publication Date
1.	Calibration of Air-Data Systems and Flow Direction Sensors by J.A. Lawford and K.R. Nippress	1988
2.	Identification of Dynamic Systems by R.E. Maine and K.W. Iliff	1988
3.	Identification of Dynamic Systems – Applications to Aircraft Part 1: The Output Error Approach by R.E. Maine and K.W. Iliff Part 2: Nonlinear Analysis and Manoeuvre Design by J.A. Mulder, J.K. Sridhar and J.H. Breeman	 1986 1994
4.	Determination of Antenna Patterns and Radar Reflection Characteristics of Aircraft by H. Bothe and D. McDonald	1986
5.	Store Separation Flight Testing by R.J. Arnold and C.S. Epstein	1986
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7.	Air-to-Air Radar Flight Testing by R.E. Scott	1992
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13.	Reliability and Maintainability Flight Test Techniques by J.M. Howell	1994
14.	Introduction to Flight Test Engineering Issue 1: Edited by F. Stoliker Issue 2: Edited by F. Stoliker and G. Bever	 1995 2005
15.	Introduction to Avionics Flight Test by J.M. Clifton	1996

16.	Introduction to Airborne Early Warning Radar Flight Test by J.M. Clifton and F.W. Lee	1999
17.	Electronic Warfare Test and Evaluation[‡] by H. Banks and R. McQuillan	2000
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25.	Flight Testing of Night Vision Systems in Rotorcraft by G. Craig, T. Macuda, S. Jennings, G. Ramphal and A. Stewart	2007[†]
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28.	Electronic Warfare Test and Evaluation by M. Welch and M. Pywell	2012

At the time of publication of the present volume, the following volumes are in preparation:

Reduced Friction Runway Testing

Safety and Risk Management

Aircraft Stores Compatibility Testing

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Test and evaluation
Threat simulation

14. Abstract
Electronic Warfare (EW) Test and Evaluation (T&E) is a complex and expensive undertaking. Practitioners must understand the subject matter to efficiently apply available test resources and cost effectively meet their test objectives. This revised EW T&E handbook provides an overview of various types of EW systems and basic test methodologies. It also describes various test resources and discusses their associated strengths and limitations. Some typical problems are identified and discussed in a Learning from Experience section. A brief overview of some test resources and facilities across NATO and Partnership for Peace countries are provided along with points of contact to aid potential customers.

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Improved test capabilities for cost-effective performance evaluation of airborne electronic warfare systems

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ABSTRACT

State of the art test capabilities are described that can enable optimised electronic warfare (EW) system development programmes for military air platforms. EW systems are key enablers of air platform survivability and the above is important as defence ministries and industry world-wide wrestle with affordability, technical and industrial challenges. The military end user needs improved capability quickly, with high availability; defence ministries want this at lowest possible cost and with minimum risk. Satisfying these requirements, while remaining in business against a background of fierce international competition and world financial crisis, is indeed challenging. Improvements are described that can enable improved technical performance and lower cost, time and risk programmes than hitherto, with emphasis on RF EW systems and the recent multi-£M upgrade to BAE Systems' EW Test Facility, with its aircraft-sized anechoic chamber. This upgrade assures a further decade of world-class UK capability for testing manned and unmanned air platforms.

NOMENCLATURE

AIRCM	advanced infra-red countermeasures (pod)
AWC	(RAF) Air Warfare Centre
CEESIM	combat EM environment simulator
DAS, DASS	defensive aids system/sub-system
DEWC	(AWC) Defence EW Centre
DE	directed energy
DIRCM	directed IR countermeasures
DT&E	developmental T&E
DTP	defence technology plan
Dstl	Defence Science and Technology Laboratory
EA	electronic attack
ECM	electronic countermeasures
ELINT	electronic intelligence
EM, EMC	electromagnetic(s), EM compatibility
EO/IR	electro-optic/infra-red
EP (ED)	electronic protection (electronic defence)
ES, ESM	EW support, EW support measures
EW, EWTF	electronic warfare, EW test facility
HITL	hardware-in-the-loop
HPM	high power microwave
ITEA	integrated test, evaluation and acceptance
LCC	life cycle cost
M&S	modelling and simulation
OT&E	operational T&E
PSI	platform systems integrator
RCS	radar cross section
RF	radio/radar frequency
RFEG	RF emitter generator (RF threat simulator)
RISS	real-time IR scene simulator
RMS	(ECM) response measurement system
RWR/RHWR	radar warning/homing and warning receiver
SE	synthetic environment(s)
SRD	system requirements document
SMS	signal measurement system
SUT	system under test
T&E	test and evaluation
UAS	unmanned air system, autonomous system
UAV/UCAV	unmanned air vehicle, combat air vehicle
URD	user requirement document
V&V, VVRM	verification and validation, requirements matrix

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1.0 INTRODUCTION

This paper identifies improved UK test capabilities for the cost-effective evaluation of EW systems, with emphasis on airborne radio/radar frequency (RF) EW equipments. It focuses on those used for air platform self-protection, more commonly known as defensive aids systems or sub-systems (DAS, DASS).

The importance of DAS to platform and aircrew survivability and, more importantly, mission success is stated. EW Systems and DAS are described and the challenges facing the EW test and evaluation (T&E) community[†] are defined. Typical customer acceptance methodologies are described. EW T&E capabilities are then described in some detail, followed by a description of recent and potential future technical developments, a number of which result from research and other investigations by these authors.

Conclusions are stated and recommendations made for selected high-benefit EW T&E developments, underpinning research and other actions which it is thought could aid defence ministries, industry and military end users better meet affordability, technical and environmental challenges of the next decade and beyond.

Some caveats apply to this paper:

- EW systems and consequently T&E equipment operate in the same technical parameter space, since all operate generally with the same multi-spectral threat environment.
  - Paper covers all system types, but concentrates, for EW T&E capabilities, on RF systems operating in EW frequency ranges.
  - No requirement or numeric in the paper is intended to be associated with any specific system under test (SUT), platform or programme.
- Directed energy weapons, although defined in NATO as a sub-set of EW, are mentioned but – with the notable exception of Directed IR Countermeasures (DIRCM) – are not covered.
- Emitter databases, essential to EW systems and associated T&E equipment, are not discussed since nationally sensitive.

2.0 SURVIVABILITY: EW CONTRIBUTION

This section sets the scene by stating survivability's importance to mission success and aircrew life expectancy, noting that 'success' in this context is also more recently and perhaps better known as 'effectiveness'. It then describes EW as a survivability component and discusses threat scenario changes faced by NATO and the UK.

2.1 Survivability – key to mission success

Survivability is key to mission success for military air platforms, whether manned or unmanned, fixed or rotary wing (helicopters). Without adequate survivability features damage or destruction will likely occur when going in 'harm's way', thus causing mission failure. This is particularly so for ground attack aircraft, where lethal threat weapon density generally increases as a function of remaining distance to target. An important distinction is that the objective of survivability features is to enable the platform and crew complete their mission, not to enable them to survive but not complete the mission. This was expressed succinctly by a now-retired MoD[‡] colleague in Ref. 1 as 'Survive to fight, not fight to survive'.

	SURVIVABILITY COMPONENT			
EW COMPONENT	THREAT AVOIDANCE	ATTACK EVASION	THREAT ELIMINATION (SUPPRESSION OR DESTRUCTION)	DAMAGE TOLERANCE
ELECTRONIC WARFARE SUPPORT (ES)	OWN & NETWORKED ESM/ELINT/COMINT, EMITTER LOCATOR SYSTEMS & RADAR/MISSILE/LASER WARNERS TO:			NO EW CONTRIBUTION – ABILITY OF AIRFRAME AND SYSTEMS TO SUSTAIN WEAPON FRAGMENT DAMAGE & CONTINUE MISSION OR, AT MINIMUM, RETURN TO BASE FOR REPAIR
	• OPTIMISE SITUATION AWARENESS • INFORM PRE-FLIGHT MISSION PLANNING • ENABLE IN-FLIGHT RE-ROUTING • FEED FRIENDLY NETWORK-ENABLED CAPABILITY	• CUE OWN RF/EOIR COUNTERMEASURES • CUE SUPPORT JAMMING – STAND-OFF – ESCORT – CLOSE-IN (e.g. UAV)	• CUE OWN WEAPONS AND RF/EOIR COUNTERMEASURES • CUE SUPPORT JAMMING • VECTOR FRIENDLY WEAPON SYSTEMS ONTO THREAT	
ELECTRONIC ATTACK (EA)	DECEPTION & SATURATION JAMMING DENY THREAT SENSORS KNOWLEDGE OF OWN PLATFORM POSITION	RF/EOIR JAMMING & DE ATTACK • DENY OPPONENT'S TARGETING & FIRING SOLUTIONS • DECOY INCOMING MISSILE OR FIRE	• STAND-OFF/IN, SELF PROJECT & ESCORT RF JAMMERS • CHAFF/FLARES • EOIR JAMMERS • ANTI-RADIATION MISSILES • DE ATTACK	
ELECTRONIC PROTECTION (EP)	OWN EW SENSORS' ANTI-JAM (COUNTER-COUNTERMEASURE) CAPABILITY PROVIDES OWN PLATFORM WITH CONTINUED PASSIVE DETECTION, IDENTIFICATION AND LOCALISATION OF THREATS			

Figure 1. EW contribution to survivability.

2.2 EW – a vital component of survivability

Table 1 defines EW and its components EW support (ES), electronic attack (EA) and electronic protection (EP), also called electronic defence (ED) in the UK.

Figure 1 shows how EW contributes to the air platform combat survivability equation, whose components are threat avoidance, attack evasion, threat elimination and damage tolerance.

Table 1
EW definitions

EW	Any military action involving use of electromagnetic and directed energy (EM, DE) to control and protect the own usage of the EM spectrum or to attack an adversary and deny his access.
ES	That division of EW involving actions tasked by, or under direct control of, an operational commander to search for, intercept, identify, and locate or localise sources of intentional and unintentional radiated EM energy for the purpose of immediate threat recognition, targeting, planning and conduct of future operations.
EA	That division of EW involving the use of EM energy, DE or anti-radiation weapons to attack personnel, facilities or equipment with the intent of degrading, neutralising or destroying enemy combat capability.
EP	Actions taken to protect personnel, facilities and equipment from any effects of friendly or enemy employment of EW that degrade, neutralise or destroy friendly combat capability.

2.3 Threat scenario changes

NATO and the UK require to project military power world-wide to protect their allies and interests. In former times this 'extended reach' aspect was achieved by *inter alia* maintaining a large presence at overseas military bases. Economic and political changes, especially in the past decade, have led to a significant reduction in these bases and a matching dramatic shift of focus to what is termed 'Expeditionary' warfare. Expeditionary forces, whether single nation or – as is often the case nowadays – in coalition with other partners, e.g. in Iraq and Afghanistan, require adequate supporting air power capability to achieve air superiority (temporary and spatially-limited

[†] For UK includes RAF (especially AWC and DEWC), Dstl, BAE Systems (fixed wing aircraft), AgustaWestland (helicopters), QinetiQ and EW/DAS and test equipment suppliers, e.g. SELEX Galileo, Thales UK, Chemring, EWST and ESL.

[‡] M.E. Hurricks, formerly head of ESM at DERA (Farnborough), then Eqpt Capability (Theatre Airspace) – Air Enablers, MoD.

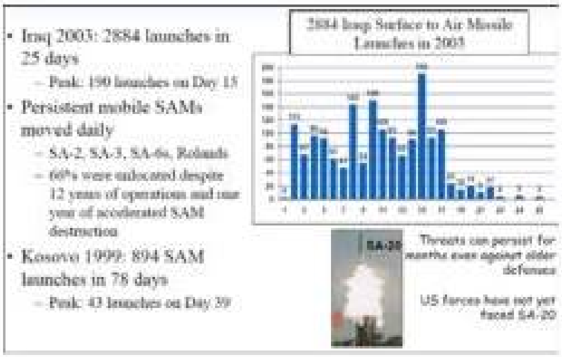

Figure 2. Example threat scenarios.
(Dr Rebecca Grant[21])

control) in the required theatre of operations. It is generally accepted that air superiority is rarely achieved and that air supremacy (total control for entire campaign) cannot currently be guaranteed, so long as man-portable heat seeking missiles continue to pose a deadly hazard to aircraft flying below 20,000ft in combat zones.

The UK and its allies world-wide, especially in NATO, now face a challenging change in threat scenarios to those typically faced in recent decades, e.g. those in Fig. 2.

NATO Research and Technology Organisation Study SAS-064, on which this lead author was a UK delegate, completed in 2008 and Ref. 3 provides an updated view of 'Requirements and options for future NATO airborne EW capabilities'. The study generated updated scenarios, see Fig. 3. The predominant change driver is the asymmetric threat[a], whose importance has grown in recent years.

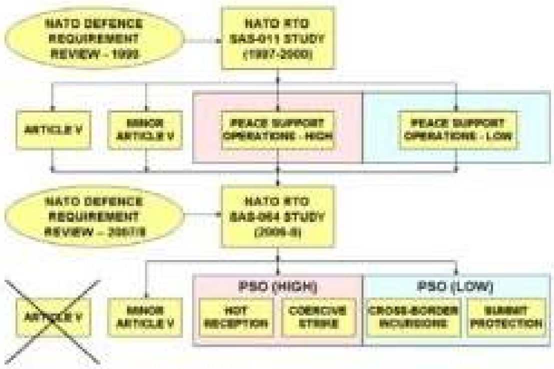

Figure 3. NATO scenario changes in past decade.

Key aspects of the change are:

- Peace support/enforcement operations pose the greatest challenge, with irregular forces and insurgents as opponents.
- Threats are generally small and highly mobile.
- Rules of Engagement are extremely tight, to minimise 'collateral damage' – non-combatant casualties.
- Current and potential opponents are now well versed in NATO EW capabilities and tactics.
- Threat systems now operate robust RF emissions control regimes to minimise attack by friendly forces, with RF-guided threats often now augmented by optical/electro-optical means. Threat systems are thus much harder to detect, identify and locate – especially with the trend for minimum RF transmission times.
- Increasing importance of network-enabled capability, as EW by itself cannot fully contain the increased threat envelope.
- Conflicts are routinely subject to intense, real-time media coverage – 'Trial by TV'. Potential adverse impact on public support for military operations cannot be under-estimated.

These changes and the drive by defence ministries world-wide for improved whole life affordability for platforms have substantially increased the importance of and requirements for EW systems, including DAS, to minimise attrition. Time-critical targeting of threat systems as (and preferably before) they engage own and friendly aircraft is now imperative. In particular, the previously important cardinal features of EW receiver systems, threat detection, identification and location, are now vital to mission success and aircrew survivability.

3.0 EW SYSTEMS DESCRIPTION

This section describes EW system types, with focus on those for the DAS sub-set of EW, which are fitted to most fixed and rotary wing military aircraft. The range of types is outlined, from stand-alone to fully integrated. Reference is made to the Eurofighter Typhoon's DASS, which has been extensively tested in BAE Systems' EW Test Facility (EWTF) and on sub-system and avionics integration rigs at their Warton, north-west UK base.

EW systems can be considered to be a super-set of the generalised DAS shown in Fig. 4. A platform's exact DAS fit is dependent upon platform type, role, mission and operational theatre, and thus not all platforms will have all components. In addition, again dependent upon the above, the capabilities of some components vary. The best example of this is EW receivers: radar warning receivers (RWR), electronic support measures (ESM) and electronic intelligence (ELINT) receivers. Although the technical performance boundaries between these has become blurred in recent years, with high-end ESM in particular approaching ELINT quality, a DAS does not currently include ELINT.

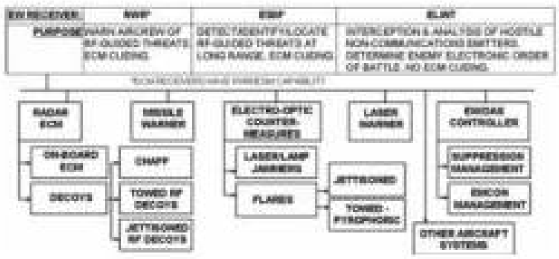

Figure 4. Generalised DAS block diagram.

Other EW components not usually part of DAS, and thus which are not discussed further in this paper, are:

- Stand-off and escort jammer pods.
- Anti-radiation missiles
- Communications intelligence receivers
- Communications frequency ESM and jammers
- Navigation/global positioning systems and data link jammers
- DE weapons, notwithstanding lamp- and laser-DIRCM, as already in service on a number of platform types.

[a]NATO AAP-6 (2009): 'A threat emanating from the potential use of dissimilar means or methods to circumvent or negate an opponent's strengths while exploiting his weaknesses to obtain a disproportionate result.' Relates to insurgency and terrorism.

Figure 5. Praetorian components.
(© SELEX Galileo 2008)

Many DAS configurations exist, usually falling into one of three primary installation types:

- Fully integrated: Usually only possible when designed as part of the platform during original development. This enables optimisation of many key EW performance parameters, e.g. antenna coverage and RF interoperability of the platform's many RF transmitters and receivers. A good example of this is the Typhoon DASS, comprising the EuroDASS 'Praetorian', see Fig. 5, the defensive aids computer and the flare and chaff dispensers and Laser Warner identified on Fig. 6 (DASS aircraft installations). The DASS is controlled from cockpit multi-function displays.
- Federated/partially integrated: Frequently the case where function and/or performance of original DAS component is enhanced and overall performance improved via better integration with other DAS components and the platforms displays and control sub-system. The Tornado aircraft is a good example:

Figure 7. Terma AIRCM pod on Tornado GR4.
(© BAE Systems 2009, all rights reserved)

  - Original GR1 variant's DAS was a loosely integrated RHWR, Sky Shadow (jammer) and BOZ-107 (flare/chaff dispenser).
  - 'Mid-Life Upgrade' GR4 variant improved performance and integration via RHWR-2, Sky Shadow-2 and BOZ-107-2, with improved Displays and Controls interface.
  - DAS improved further in 2009 by addition of Terma's Advanced IR CounterMeasures pod, see Figs 7 and 8, adding missile warner and additional flare/chaff dispensers.
- Stand-alone DAS: Often a podded solution, this is an attractive way of introducing a new or replacement DAS to a platform,

Figure 6. DASS equipment locations on Typhoon. (© BAE Systems 2009, all rights reserved)

especially – from an affordability standpoint – when operational requirements do not require DAS for every mission. Such 'role fit' DAS solutions are particularly attractive for Unmanned Air Systems (UAS)[1].

4.0 CHALLENGES – CURRENT AND FUTURE

Many challenges face industry, defence procurement agencies and military end users in their quest to help the warfighter meet today's and tomorrow's military objectives at minimum whole life cost – both fiscal and aircrew. These challenges and the UK strategies for addressing them are described in the *Defence Industrial Strategy*[(4)] and *Defence Technology Strategy*[(5)] (Fig. 9). These remain valid pending update after the post-general election Strategic Defence and Security Review.

Extracts from Refs 4 and 5 and MoD's Defence T&E Strategy[(6)] that impact EW T&E[2] are presented here, with comment as appropriate.

- EW's vital and integral role in military operations across the spectrum of conflict is re-confirmed and likely to remain so for the foreseeable future. EW – all aspects across all platforms – is identified as a defence priority technology.
- All areas of EW are stated to be of UK sovereign importance: 'UK national capability to research, design, manufacture, programme, supply, integrate, test and evaluate and optimise performance. Intelligent customer status.'
- Key UK 'cross-cutting technology capabilities' are identified, including EW, survivability, sensors and mission systems.
- Key role of 'platform systems integrator' (PSI) introduced, with BAE Systems the PSI for aircraft, ships and armoured fighting vehicles, and AgustaWestland for helicopters.
- Integrated survivability is systems engineering methodology to achieve optimum and affordable survivability, enabling a mission to be completed successfully in a hostile environment. Suite of models and T&E capabilities required to optimise methodology.
- Need for obsolescence-proofed solutions, with rapid insertion of innovative technology in incremental upgrades, rather than in major 'mid-life upgrades' previously seen on platforms.
- PSI and systems engineering challenges increasing as a result of increased platform longevity and continuing (and often accelerating) technology development – especially electronics.
- Long-term goals defined, including through-life capability management, its application to EW T&E capabilities and sustainment of key UK skills and capabilities.
- Underpinning deep understanding of threats required. EW T&E capabilities required to support assessment of real threats.
- MoD-led groups, the Towers of Excellence bring together key players in the UK defence industry and leading UK academic establishments. The EW ToE has been operational since 2004.
- Artificial T&E: laboratory analysis, experimentation and modelling and simulation (M&S) are playing an increasingly important role in T&E activities. Undoubtedly reducing the need to conduct physical equipment and system testing, they are not a complete solution. A shift in the balance between laboratory and physical testing is inevitable, but specialist and dedicated T&E ranges, facilities and supporting personnel will still be required. The challenge is to ensure the optimum mix is delivered and, more importantly, sustained.
- Vision realisation requires optimisation and development of existing UK T&E facilities, coupled with analysis of other opportunities. For example: greater mobility and deployability

Figure 8. Flare dispensing from AIRCM pod.
(Unknown 'spotter' photograph from Internet)

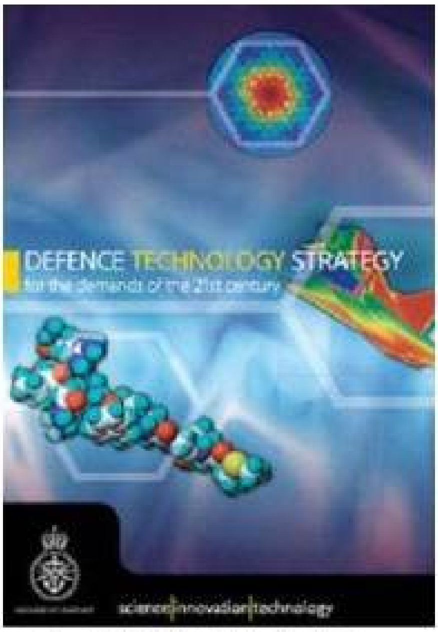

Figure 9. *UK Defence Technology Strategy.*
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Figure 10. UK UCAV demonstrators.
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[1]UAS, which also means Unmanned Autonomous Systems, include UAVs (Unmanned Air Vehicles) and UCAVs (Unmanned Combat Air Vehicles).
[2]Reference 6 definition: 'The demonstration, measurement and analysis of the performance of a system, and the assessment of the results.'

Table 2
Challenges facing the EW T&E community

AREAS WHERE THE EW T&E COMMUNITY COULD ENABLE OR CONTRIBUTE TO CHALLENGE SOLUTIONS	APPLICABLE CHALLENGES: AFFORDABILITY	SURVIVABILITY	INDUSTRIAL	ENVIRONMENT	UAS (UAV/UCAV)
OPTIMISATION, DEVELOPMENT AND SUSTAINMENT OF EW T&E FACILITIES					
• Bolster chamber and laboratory test capability robustness: ➢ To trap more problems prior to flight, saving T&E cost/time by reducing number of fly-fix-fly iterations required ➢ To better support R&D, evaluation of prototype technical solutions and EW Technology Demonstrator Programmes ➢ By generating more operationally realistic and measurable RF/IR/RO threat environments in laboratory/chamber	G	A	R	G	G
• Enhance operational support: ➢ Improve Mission Data Validation quality by use of 'mission rehearsal' quality complex RF/IR/EO emitter scenarios ➢ Enhance countermeasures development/optimisation process via use of anechoic chamber	A	G	R	A	G
• Where viable, ensure complex EW T&E equipments are portable/transportable	G	R	A	R	G
• Network UK EW T&E, Synthetic Environment (SE)* and M&S facilities to realise potential benefits: system requirements capture and optimisation, system development risk minimisation, training, tactics development	G	G	A	R	G
• Closer cooperation between key UK T&E assets, *i.e.* EW Tactics Range - RAF Spadeadam, DEWC and EWTF	G	G	G	R	G
• Cooperate with overseas EW T&E agencies and facilities where appropriate and UK-beneficial	R	G	A	R	G
• Ensure long-lead capabilities available in time: anticipate Urgent Operational Requirements (UORs), upgrades and future EW fits – including upcoming 'digital from back of sensor' systems, see Ref.(7)	G	G	G	R	G
• Focus on critical features, to assure required key UK sovereign EW T&E facilities and viable export support	G	A	G	R	A
RAPID DEVELOPMENT, INSERTION & ACCEPTANCE OF EW SYSTEMS IMPROVEMENTS					
• Support increased EW acceptance process use of SE and M&S, by providing facilities for robust validation of EW models	G	G	G	R	G
• Identify, and then help reduce, technical, programme and cost risks from the earliest possible stages of acquisition	G	G	G	A	G
• Help better understand EW-Survivability cost-benefit trade-offs for performance verification and system acceptance	G	G	A	R	G
• EW Sensor placement optimisation via modelling and sub-/full-scale testing in anechoic chamber, to prevent, reduce, resolve problems with EW sensors/effectors, data links, communication systems and other RF sensors	G	G	A	R	G
• Laboratory/chamber R&D to understand mismatches between flight and ground test results	G	G	G	A	G
• Generate capability to perform mission rehearsal/optimisation in anechoic chamber's secure RF environment	G	G	A	R	G
REDUCED COST AND ENVIRONMENTAL IMPACT OF EW T&E AND FACILITIES					
• Less flight testing and ground engine running = reduced fuel cost and carbon footprint	G	R	A	G	G
• More energy-efficient ground test facilities, *e.g.* RF threat simulators	G	R	A	G	G
• Reduced whole life cost via reliability enhancements that improve availability for testing and reduce spares holdings	G	R	A	G	G
• Reduced RF environmental pollution: radio/radar/EW, EM Compatibility (EMC), lightning strike tests in chamber	G	R	A	G	G

Codes: G Strong contributor A Medium contributor R Minor contributor or Not Applicable

of complex T&E equipment; networking of T&E and other facilities; greater use of M&S.

- MoD's medium term strategic intent is to retain UK T&E capability, but look for overseas cooperation where appropriate. European Defence Agency work may lead, in due course, to longer-term, European T&E capabilities' consolidation strategy.
- 'Taking forward the *Defence Industrial Strategy*, challenges for change' core task is to provide 'equipment that are: fit for the challenge of today; ready for the tasks of tomorrow; capable of building for the future'.
- MoD's vision for its T&E capability is 'cost-effective accurate assessment of military capability through-life.'
- Need for optimisation of T&E assets (both within and external to MoD) and use of new methods as they emerge.
- Delivery of T&E capability is co-ordinated but not managed by the Defence Equipment and Support (TEST) Team.

UAS are an emerging system in aerospace and there are powerful drivers for their development and employment. Significant challenges exist to achieving advanced combat-capable UAS. These encompass those of manned aircraft, with additional complications, e.g. miniaturisation; installed RF and electro-optic/infra-red (EO/IR) sensor performance; and interoperability of multiple RF transmitters and receivers in very close proximity. UCAVs pose a particular challenge, as capable DAS is required to enable survivable solutions for long range penetration and persistence in hostile airspace. Figure 10 shows UK UCAV technology demonstrators.

As this paper concerns EW T&E, the whole range of challenges is not covered herein. Rather, a consideration has been made of areas where, see Table 2, the EW T&E community could add value by helping meet these aerospace innovation challenges. Most challenges identified are applicable to all military aircraft types and many are also applicable to the land and sea domains.

This paper's remainder demonstrates areas where the EW T&E community has already developed improved test capabilities to help meet some of the above challenges. It also identifies further research, developments and other actions that could improve on challenge resolution performance to date.

It is useful at this point to clarify subtle differences between M&S and SE, which are used extensively within Refs 4 and 5, where both are seen to be enabling capabilities that can add significantly to effectiveness and value. As often seen with terminology used across nations and between agencies within those nations, different views exist on precise meanings. For this paper the definitions in DoD 5000.59-M, 'DoD Modeling and Simulation (M&S) Glossary', per Ref. 8, are used. These definitions are stated below:

- M&S is 'The use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions. The terms 'modeling' and 'simulation' are often used interchangeably.'
- SE is: 'Internetted simulations that represent activities at a high level of realism from simulations of Theatres of war to factories and manufacturing processes. These environments may be created within a single computer or a vast distributed network connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioural models. They allow visualisation of and immersion into the environment being simulated.'

In UK's MoD Acquisition Framework[9] M&S/SE is also called 'modelling, simulation and synthetic environments (MS&SE)'

5.0 SYSTEM ACCEPTANCE

This section outlines methods used to achieve UK customer acceptance of EW systems. These methods include EW systems testing in the laboratory, in the anechoic chamber, on open air sites and via flight test. An EW T&E process overview is also provided.

5.1 Acceptance philosophy

Acceptance of defence products by UK MoD is well defined and is comprehensively described in the acquisition operating framework[9] under 'requirements and acceptance'. The set of requirements and acceptance products include user requirements document (URD), systems requirement document (SRD), Integrated Test, Evaluation and Acceptance (ITEA) Plan, and Verification and Validation (V&V) Requirements Matrix (VVRM). The ITEA process is indicated in Fig. 11.

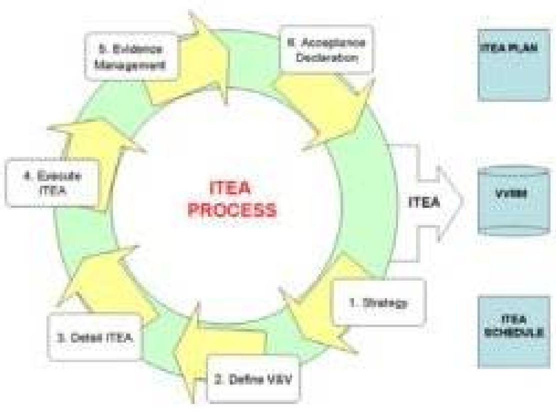

Figure 11. MoD ITEA process.
(From Ref. 9)

V&V is defined elsewhere, e.g. Section 5.1 of Ref. 10. Verification is PSI-conducted, supported by equipment suppliers, and Validation is conducted by military end users. Verification seeks to confirm platform, systems and equipments meet their specifications, as derived from the SRD. When augmented by certification, which includes independent assessment of safety evidence (usually without further testing), this leads to Release To Service and acceptance off contract. Validation is the process by which the user evaluates the delivered solution's fidelity against the URD and assesses fitness for purpose, leading to operational readiness.

Although views differ on terminology from country to country and inter-agency, verification in the UK is taken to comprise:

- Equipment performance qualification against specification, usually conducted by the equipment supplier.
- Sub-system performance verification by the supplier or PSI, dependent on contracting arrangements.
- System- and platform-level performance verification by the PSI.

Within UK final verification prior to customer acceptance is usually all conducted by the PSI, with equipment supplier support during final acceptance testing. Final certification, usually consisting of a statement of design and declaration of design and performance, is also done by the PSI and provided to the customer, to satisfy national and destination country certification requirements.

5.2 Acceptance types and methods

Industry elements of the VVRM are usually embedded in equipment contract specifications as a specification verification matrix, also called verification cross-reference matrix/index. They can also appear separately – still in line with ITEA requirements – in verification test methodology documents. These describe who will verify each specification element, how (what verification type and method) and with what T&E facilities. Construction of the VVRM is also an important specification check – the question 'Is this requirement testable?' must be answered.

Key aspects are that:

- Customer requirements each map to specification item(s).
- Each item is assigned one or more acceptance method and type by which adequate verification can be achieved, see Table 3.

T&E is sub-divided into two categories. National definitions differ but these are generally understood: that conducted during the:

- Developmental T&E (DT&E) phase covers development and

Table 3
Verification types and methods

TYPE	METHOD
INSPECTION	• Physical inspection, visual verification
	• Document review
	• Read-across by analogy, where prior evidence alone is used to fulfil a requirement
ANALYSIS	• M&S, e.g. mathematical, statistical, electromagnetic, physical
	• Read-across by evaluation, where prior evidence is used to partly fulfil a requirement
	• Technical evaluation of equations, charts, reduced and/or representative data
TEST	• Laboratory – software test, rig test (supplier), rig test (PSI)
	• Anechoic chamber (specialist equipment)
	• Aircraft ground test, e.g. EMC
	• Flight test (local or dedicated range)
DEMONSTRATION	• Un-instrumented rig or aircraft test where requirement is met by observation alone

gathering of verification evidence. The PSI (or EW equipment supplier, dependent on contracting arrangement) is responsible for this testing.

- Operational T&E (OT&E) phase, when the EW system is accepted off contract and released to service, covers operational evaluation, including tactics development. This is mostly flight testing, conducted by the military end user, usually with support from the PSI and EW equipment supplier.

Variations exist, e.g. acceptance T&E and qualification T&E, but for this paper they are considered to be sub-sets of the above.

Notes to Table 3:

- In line with cost- and time-effectiveness requirements, most specification elements are usually verified during the extensive equipment qualification phase prior to equipment delivery to the PSI. Thereafter, the quantity and breadth of testing generally reduces as one moves from sub-system to avionics integration rig, and thence from aircraft ground testing to on-range flight testing.
- Read-across is a cost-effective route for gathering verification evidence. For equipments already fitted to another platform and those that are sometimes called 'Vanilla', i.e. commercial, off-the-shelf equipment with no modifications, verification by similarity or read-across can be used. This is, however, often limited to environmental qualification, as required equipment performance is usually platform-specific and read-across from other programs is often restricted by export limitations.

5.3 EW T&E process

While this paper deals primarily with EW T&E capabilities, it is important to also address the EW T&E process itself when targeting enhanced capabilities that offer promise of step improvements in EW system development and acceptance timescales, cost and risk.

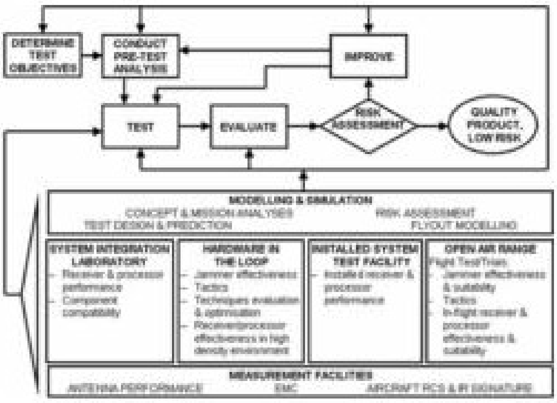

Figure 12. EW T&E process
(adapted from Refs 11 and 12)

While there does not currently exist a universally accepted standard EW T&E process, two related documents suffice to provide a good view of what such a standard process might include. These are the:

- NATO process document 'electronic warfare test and evaluation'[11]. Its focus is the processes, techniques, facilities and goals of T&E of modern EW systems. It is undergoing 2009-11 review and update under the NATO RTO SCI-203 task†.
- US Air Force Manual 112 'electronic warfare test and evaluation process – direction and methodology for EW Testing'[12]. This document was rescinded by the USAF in August 2008 and it is understood that the USAF Flight Test Center has been tasked with its update.

Table 4
Test locations and missions

Test location and primary test mission
Laboratory (RF, Intermediate Frequency and digital-level):
● R&D and concepts evaluation. Note: Often need threat simulation capability enhancement to be able to develop new or 'next generation' EW receiver systems/upgrades
● Requirements definition and system performance modelling
● Hardware In The loop (HITL): Equipment/sub-system development and qualification
● Uninstalled sub-system performance verification (usually over full ranges of performance)
● Integration with other platform avionic systems; further development and un-installed performance verification, conducted in Systems/Avionics Integration Laboratory
● ESM-ECM performance optimisation *vs* specified threat environment
● Evaluation of new/upgraded threats and countermeasures development
● Development, evaluation and clearance of EW upgrades
Anechoic Chamber:
● Platform-system integration. Further sub-system and integrated avionics system development
● Installed system performance verification, including SUT irradiation with 'war-mode' and other signals not allowed to be transmitted in the open air
● Fault/anomaly investigation, isolation and solution confirmation
● Airframe-systems aspects of EW upgrades' development, evaluation and clearance
Open air test site:
● Free field irradiation of aircraft-installed SUTs for cases where anechoic chamber tests not viable or unacceptably limited, e.g. antenna polar diagrams and ESM-ECM beam-forming measurements (far field considerations)
● Whole platform EMC tests
● Platform radar cross section measurement
Flight test range:
● Residual installed performance verification tests for aspects not acceptably testable using above locations/methods
● Development and performance verification of aspects not ground-testable, e.g. combinations of tactics, flare/chaff dispensing, on-board RF jamming and towed RF decoys
● Evaluation/optimisation of EW system man-machine interface under flight conditions
In-service support (laboratories and 'open air' training ranges):
● Mission data validation prior to and during training, operational evaluation and combat
● EW hardware/firmware and algorithmic software performance optimisation
● Post-maintenance/pre-flight check-out
● Evaluation/resolution of operational problems
● EW/countermeasures/tactics effectiveness evaluation/optimisation
● Mission rehearsal and aircrew/operator/maintainer training

† This lead author and his counterpart at the Benefield Anechoic Facility, USA, are co-authors of the SCI-203-updated handbook

Figure 12 gives a top-level view of the EW T&E process. Both documents highlight the benefits to be had from optimising the balance of M&S (T&E without the SUT), ground testing (laboratory, chamber and open air site) and flight testing on open air ranges.

A number of key messages emerge from the two documents:

- Primary test philosophy is predict-test-compare, not fly-fix-fly
- Open air range tests are considered the most costly and M&S the least.
- It is far cheaper to trap and fix EW problems as early in the life cycle as possible, than wait until flight testing.
- Better still to prevent the problems by using M&S/SE and prototype testing in laboratory and chamber.
- Emphasis on M&S and ground test prior to flight test.
- Optimal approach is decreasing number of better quality trials as the programme proceeds from M&S through measurement facilities, system integration laboratories, HITL facilities, installed system test facilities (e.g. EWTF) to more focused flight trials on open air ranges.

6.0 EW T&E CAPABILITIES

This section describes T&E capabilities†‡ required to support EW system design, development and subsequent customer acceptance.

6.1 EW T&E facilities and equipment

Facilities and equipment are described with reference to terminology used in Refs 11 and 12, with commentary and examples from BAE Systems and other agencies. The range of facilities is shown in Fig. 12 and a non-exhaustive list of strengths and limitations is given in Ref. 12. Test missions by location are summarised in Table 4. The following sub-sections describe EW T&E facilities and equipment, categorised into internationally recognised classes.

6.1.1 Modelling and simulation

M&S is used to:

- Demonstrate system performance for elements that are either too complex or too expensive to verify by testing.
- Where test repeatability is difficult or where tests would yield unacceptable error bounds.
- To supplement testing by interpolation between sparse data points or to extrapolate from measured data.
- Prove design concepts prior to final testing.

Most M&S undertaken as part of the design verification process is currently performed by equipment suppliers, who provide outcomes as acceptance evidence to the PSI. An area of promise is Computational EM Modelling, where modern computing power and innovative codes offer useful design optimisation and risk reduction for RF antenna installations on platforms.

Notable issues with M&S as relevant to EW are:

- Simulation fidelity and model validation, i.e. how faithfully they represent real threats and EW equipments and their performance.
- Modelling of EW antennas, systems and intra-platform cabling is not sufficiently robust to maximise contribution to acceptance.

There is a continuing US and European thrust to move EW T&E toward ground test and M&S. This work, which requires extensive scenario modelling and the increasing use of EW equipment models, offers great promise in reducing not only the expensive flight testing phase, but also overall EW system development and mission data validation timescales and costs. There remains, however, doubt that some aspects, e.g. RF and IR jamming and other countermeasure effectiveness, will ever be fully cleared by M&S alone, i.e. without some residual element of flight trials.

Figure 13. EW equipment on avionics integration rig.

6.1.2 Sub-systems and avionic integration laboratories

These are also called Systems Integration Laboratories, although typical EW/DAS rigs in the UK also fall into the HITL facility category (next sub-section). Figure 13 shows EW equipment on a typical avionic integration rig.

Testing performed at sub-system level utilises DAS equipments in a laboratory environment on a 'spread bench', with all other aircraft data supplied via simulations generated by an external control computer. At BAE Systems this computing capability, known as Advanced Data Acquisition and Simulation System or Target Rig Computing Facility, also serves as master test controller and provides non-RF data acquisition and analysis. EW Receiver stimulation is performed by threat simulators such as the CEESIM. An ECM Response Measurement System (RMS), e.g. Signal Measurement System (SMS), is utilised to capture, record and analyse the RF responses from the ECM element of the DAS. Note: CEESIM and SMS are products of Northrop Grumman Amherst Systems Inc ('Amherst').

Once the DAS has reached suitable maturity it is integrated by the PSI with other sub-systems, e.g. displays and controls, on an avionic integration rig. BAE Systems at Warton has several sub-system and integration laboratories, covering Typhoon, Tornado and Nimrod MRA4 EW suites. System-level performance verification testing is conducted using the EW equipments once integrated with the other real aircraft equipment on the rig. Once again EW receiver stimulation is performed by a threat simulator but the level of testing is reduced as most of the individual equipment and sub-system performance has already been proven by the earlier verification and qualification phases at the PSI and equipment supplier.

All verification tests conducted on these rigs is traceable back to the original customer requirement through the VVRM. Integration rigs are continually utilised throughout the platform's life to prove software and hardware changes and to re-test system fixes prior to release to the aircraft or to the customer.

6.1.3 Hardware-in-the-loop facilities

Although sub-system and avionic integration rigs include, by definition, real hardware-in-the-loop, generally understood HITL facilities are secure (usually screened or anechoic) indoor facilities that enable un-installed testing of EW techniques against simulation of threats or real threat hardware. Whereas sub-system

† Reference 4 definition: A Test and Evaluation (T&E) capability is a combination of facilities, equipment, people, skills and methods, which enable the demonstration, measurement and analysis of the performance of a system and the assessment of the results.

‡ Reference 6 definition: The people, assets and processes to undertake evaluation with sufficient accuracy and timeliness to assure provision of through-life military capability.

and avionic integration rigs generally do open-loop EW testing. HITL facilities have the capability to do closed-loop testing, where own EW system effectiveness can be assessed and optimised against threat system sensor systems, and the EP of own EW systems and sensors can be assessed against hostile jamming equipment.

A good example is the US Air Force EW Evaluation Simulator, which develops and operates validated, high fidelity RF and IR threat simulators that evaluate the effectiveness of US and Allied EW systems in a controlled, ground-based laboratory environment. Simulated real-time engagements are conducted at actual frequencies and wavelengths, incorporate hostile operator-in-the-loop effects and produce end-game data, e.g. miss distance. Testing is accomplished in fully-dynamic, distributed EM battlefield environments.

6.1.4 Measurement facilities

These are used to provide data that cannot be modelled adequately. In some cases, for example antenna pattern measurement, they provide data for validation of M&S used in the V&V process. Platform-level measurement facilities used during EW development include EMC (open air test sites and anechoic chambers), radar cross section (RCS) and IR signature measurement. Figure 14 shows typical examples.

6.1.5 Installed system test facilities

These provide an electromagnetically secure environment for the individual and end-to-end evaluation of EW systems integrated with or installed on the host platform. They comprise:

- Aircraft-sized RF anechoic chambers, in which free space RF radiation is used to stimulate the SUT and its responses are measured and evaluated.
- Shielded hangars, e.g. at Naval Air Station Patuxtent River (USA). While very good for much EM testing, these are lower performance than aircraft-sized anechoic chambers and thus tend not to be used for the most nationally sensitive EW T&E.

Their main purpose is to evaluate integrated avionic systems in installed configurations to verify specific, platform-level performance against specification. Chamber cardinal features are indicated in Table 5. These chambers can also be used:

- For IR/UV/Laser, EMC and interference, lightning strike, RCS and RF interoperability (including antenna isolation) testing of installed EW and other RF transmit/receive systems.
- To support EW developmental (verification) and operational (validation) flight testing by providing a pre-flight check-out and post-flight analysis capability.
- To support evaluation of closed-loop performance against threats in a free-space environment.

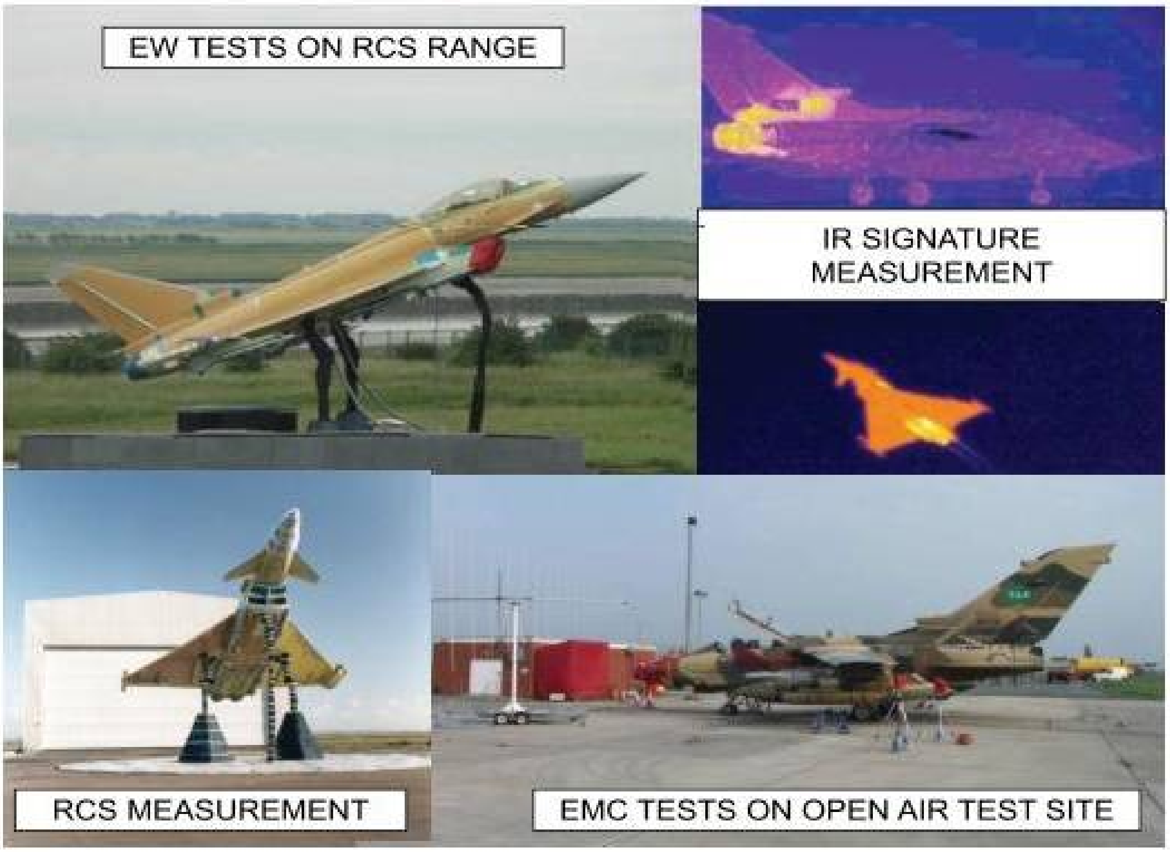

Figure 14. Measurement facility examples.

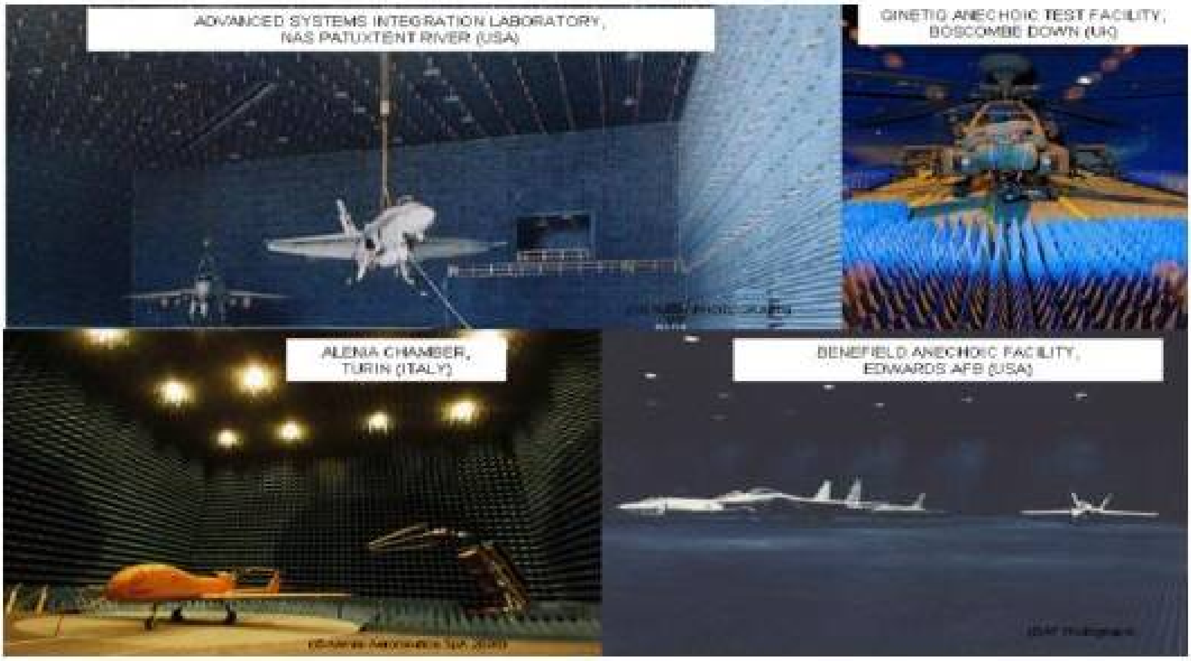

Figure 15. Example EW anechoic chambers.

Table 5
Cardinal features of EW anechoic chamber facilities

FEATURE	COMMENT
Chamber size	Minimum size around 28 × 18 × 8m, largest known chamber is 80 × 76 × 21m.
Shielding and quiet zones	Usually ≥100 dB over at least 0·5-18GHz. TEMPEST grade. Quiet zones: one or more, dependent on chamber size.
Turntable and crane	Typically in range 30-114 tonnes (turntable) and 30-40 tonnes (crane).
Below ground room	Most have laboratory, data collection or services room below the chamber.
RF/IR threat simulators	All have RF threat simulators, usually CEESIM, AMES or by EWsT. Some have communications, navigation, IR scene simulators, radar target generator.
ECM response measurement and analysis	All have some capability, from independent Equipment (spectrum, vector network, Pulse modulation analysers) to comprehensive systems like the SMS.
Data acquisition and simulation	All have some capability, for RF, digital and other signal recording and to provide signals to the platform to enable 'flight' simulation.
Aircraft and other services	– Cooling, hydraulics, pressurised air, ground power for aircraft. – Fire suppression, control room, CCTV and video recording – Radar absorbent material (RAM) temperature monitoring. – Enclosed aircraft preparation area (some).
Location	Most facilities are adjacent to taxi-way, the flight line or a runway.

- For platform (EW/non-EW) susceptibility testing against high power microwave (HPM) and other DE threats.

RF threat simulators are key laboratory and chamber equipment. Quantity of RF channels, a significant cost driver, governs their ability to generate complex threat environments. Results of an update to the Ref. 10 survey of the quantity of RF channels per simulator is given in Table 6. Chamber installations tend to have simulators with at least eight RF channels.

There are few aircraft-sized EW anechoic chambers in the world. A selection is shown in Fig. 15, in addition to the EWTF, which is covered in section 7. Others exist, e.g. PRIMES (Eglin, Florida, USA), Lockheed Martin (Fort Worth, Texas, USA) and at Dassault (Istres, France).

Table 6
Quantity of RF channels per simulator

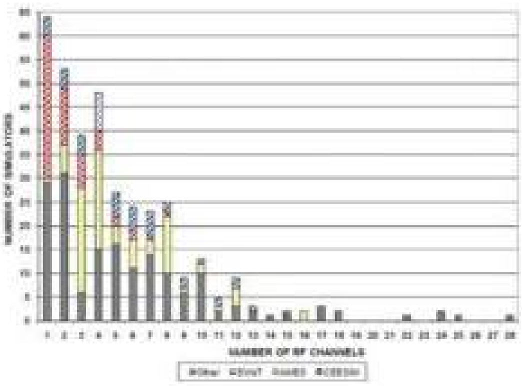

Figure 16. Mallina UV (missile launch) simulator.
(© ESL Defence Limited 2009)

Figure 17. Apache over SA-8 at RAF Spadeadam.
(© UK Crown copyright 2009)

6.1.6 Open air ranges

EW T&E in flight is sub-divided into DT&E and OT&E. Both are usually conducted on specialist open air ranges. DT&E flying is the final stage of acceptance testing and is the final performance verification undertaken prior to customer delivery. This testing not only examines system performance when installed in the airframe, but also looks at safety in terms of, for example, safe separation of flares, chaff and towed decoys.

Although not strictly flight testing, EW pre-flight checks using flight line test sets are usually limited to confirmatory checks. Such test sets, dependent upon capability, can be utilised for system testing but can be limited when compared to chamber- and laboratory-based threat simulators. Examples include the Microkim RSS-2000 Radar Signal Simulator for ESM and RWR and the Mallina UV (missile launch) simulator for missile warners, see Fig. 16.

All known open air ranges are owned and operated by the military, some with civilian contractor support. Most have a combination of multiple real threat systems, manned/un-manned high fidelity threat simulators ('emulators') and other (lower fidelity) simulators. EW T&E on these ranges is widely agreed to be the next best thing to war-fighting as this is the only 'facility' which provides a wholly realistic flight environment.

Among a number of UK T&E ranges, that of most relevance to this paper is the EW tactics range at RAF Spadeadam[13], see Fig. 17. This range, covering 9,600 acres in Cumbria, northern England, has adapted in recent years from its original tactics development role to be a wider remit, tri-service EW training facility. It now supports warfighters face changing threat scenarios (see Section 2.3). It provides an environment for training in time sensitive targeting; close air support; forward air control; intelligence, surveillance, target acquisition and reconnaissance; in addition to EW and airborne platform protection. Aircrews can experience a dynamic and complex threat environment, including movable threats.

Key benefits of open air range:

- The full range of tactics and countermeasures against given threats can be explored, including dynamic closed-loop effectiveness testing against threats.
- They provide real-world phenomena that cannot be repeated or is difficult to repeat in the laboratory or chamber environment. These include terrain, inter-platform multi-path, chaff dispersion and realistic civilian communications and radar environments.
- They can be used to gather data for validating threat simulators and M&S tools and processes.

Drawbacks of open air range:

- Flight testing is expensive, especially when compared to chamber and laboratory testing.
- Range threat densities and mixes are usually very limited compared to war, due to the high life cycle cost (LCC), of real threats, emulators and simulators.
- Threat scenario flexibility is limited (governed by the range location) and results are not easily repeatable.
- Flight testing is logistically difficult, especially for out-of country ranges. The US EW ranges, e.g. electronic combat range, China Lake (California), are arguably best, but Europe has very capable ones at RAF Spadeadam and Polygone Range (Germany/France).
- Range time slots for DT&E are usually limited due to great demand by military users for training and OT&E. This underscores the importance of gaining maximum confidence from ground testing and M&S/SE. The drawback is, in fact, usually double when a test fails: the flight has to be repeated after problem investigation and resolution and, as important, the valuable range slot has been denied to another user.

From a DT&E viewpoint, chambers and laboratories are much better capabilities than open air ranges for RF EW testing as follows:

- Much cheaper and logistically easier than flight testing, when overall trials' costs are considered.
- Operationally representative threat densities, mixes and scenarios are achievable, albeit currently with lower simulation fidelity than real threats (noting that chambers can do some SUT tests using real threats when they are made available).
- Scientifically high test repeatability, due to tightly controlled test environment, especially in anechoic chambers.

Developments described in this paper, if enacted, will shift the balance from EW flight testing further in favour of more ground testing and M&S. It may also enable some OT&E to be conducted via ground test. In this way residual flight testing can be more focused and have a much higher success probability, as many test points will then be confirmatory rather than experimental in nature.

There will, however, always be a need for flight test of EW systems, especially for development of tactics and training in support of operations and exercises. Ranges like RAF Spadeadam and the capabilities of NATO's Joint EW Core Staff[†], see Fig. 18, are essential to optimising survivability and mission success probability.

[†]www.jewcs.nato.int

Figure 18. NATO JEWCS Training/T&E capabilities.
(NATO JEWCS photograph)

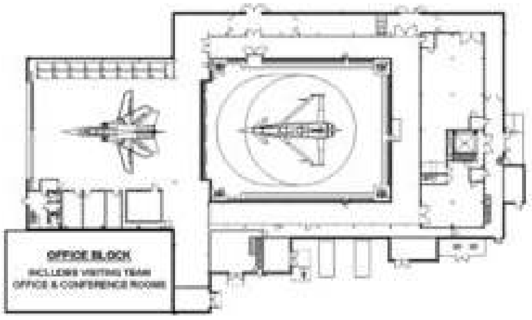

Figure 19. Layout of EWTF complex.

Table 7
Pre-upgrade EWTF capability – key EW T&E features

EWTF Complex:

Anechoic chamber and sub-system test laboratory
Offices, two conference rooms, secure visiting team room
Secure vault (up to top secret: multi-nation partitioned)
Peritrack access from EWTF to nearest runway (<300m)

Shielding:

Shielding >100dB from 10kHz to 40GHz
TEMPEST grade, fully welded shield
Quiet Zone 18·2m diameter, 9·5m high
Two Quiet Zone locations: centre and 4·7m offset toward main door
Quiet Zone performance (up to 40GHz):
- Monostatic: –90dB
- Bistatic: –80dB

Laser/Electro-Optic/IR/UV testing: Class 4 laser-tight, double safety door interlocks

RF transmission and reception:

Six threat site multi-antenna stacks:
- Four corners, at floor level; one at centre of wall opposite door; one at top of that wall
- Steerable stacks, with laser pointer
- Multiple transmit and receive antennas per stack

Basic threat simulation configuration:
- 21 RF amplifiers (microwave/millimetre wave)
- Variety of other amplifiers, up to 18GHz 1kW CW and 9kW pulsed (4%)

Basic RF signal reception configuration:
- ECM response measurement
- Threat simulator output verification
- Chamber RF environment characterisation

Anechoic chamber dimensions:

Shield: 30m long × 23·8m wide × 13·5m high
RAM-tip to RAM-tip: 29·1m × 22·9m × 12·5m
Main door: 16m wide × 12·5m high
Two human-sized access doors
One double door for equipment access.

Support services:

30 tonne crane and 30 tonne turntable: independent and synchronised operation, 0·1 to 1·0°s-1 rotation rate each
70 tonne static capability
Sub-turntable laboratory and services room
Power: Single/3Ø UK, 115/200V 400Hz 3Ø aircraft
Hydraulics: Max 280 bar, 180 litres/minute
Compressed air: >10 bar, 22m^3/minute
Static and mobile CCTV and video recording
Fire Detection: Smoke and heat, 4 zones, 2-stage alert. Thermal cameras for RAM temperature monitoring
Fire suppression: water deluge: 1 ton/second for 3 minutes

Instrumentation:

11 channel AMES-II, by ASDI (now Amherst)
- Microwave/millimetre wave channels, 2 high speed synthesisers
- 256 emitters and 256 platforms simultaneously at RF
- Modes: stand-alone, close-coupled and fully controlled by external control computer

ECM response measurement system, by TRW/MASS:
- Wide-band cueing receiver in microwave band
- 10 MHz narrow-band, high speed tuner

EW measurement system:
- Microwave/millimetre wave, 10 MHz bandwidth receiver
- 25 MHz sampling ADC, 90 minute recording

Other: Microwave laboratory analysers, data acquisition and simulation equipment, bus analysers, etc.

6.2 The human element

The EW field is a complex one, requiring high levels of specialism and experience in a number of sub-disciplines, *inter alia* microwave engineering, mission systems engineering, platform design and development, electromagnetics and rig and on-aircraft T&E. Substantial resource and commitment is required to support rapid EW capability insertion on platforms.

For example, within BAE Systems, Military Air Solutions Division, which has 20 years experience of EW prime contracting, there are ca. 60 engineers involved in EW activities, including specialists. Besides engineers embedded in aircraft project teams, there is a pan-project EM Engineering Department, which operates the EWTF and supports all EW and related areas: Installed antenna performance, EMC and hazards, lightning strike, nuclear/non-nuclear EM pulse and radar/IR signatures. This department has EW specialists and engineers with over 160 years of experience in R&D, studies, systems design, development, T&E and in-service support, at equipment, sub-system rig, integration rig and on-aircraft levels. They have links with the AWC/DEWC and Dstl and are recognised experts in the high value EW test equipment that is essential to support performance verification, EW mission data validation and ECM technique analysis and optimisation.

As defence programme activity becomes more sporadic in the UK, maintaining such specialist teams becomes more challenging. This is exacerbated by off-shore procurement of defence systems for which the UK does not have sovereign control. The UK *Defence Industrial Strategy*[4] recognises this as a challenge, see section 4. Resolution of this challenge is considered crucial if the many potential benefits described in this paper are to be realised. It is thought the answer lies within long term partnering agreements that are still under consideration by MoD and Industry.

7.0 EWTF CAPABILITY DEVELOPMENTS

This section outlines the EWTF's history and describes its recent major upgrade, highlighting aspects which can aid Industry, Customers and military end users in addressing the challenges previously identified. Potential future developments, underpinning research and other investigations are described.

7.1 EWTF history

The EWTF was specified in 1992/3, its construction was contracted in June 1994 and it became operational October 1997. It was originally designed for EW testing of the Eurofighter Typhoon aircraft and other, similar-sized platforms. Its pre-upgrade EW T&E capability is summarised in Table 7 and Fig. 19.

In addition, the EWTF benefits from ready access to:

- Full airfield support services, including safety case specialists, trials preparation, test investigations and post-test analysis.
- Manufacturing facilities for specialist items to support aircraft and other SUTs in the chamber.

In conjunction with the later addition of a full threat lightning strike simulator, other EM and RCS test equipment and comprehensive Computational Electromagnetics support capabilities, the EWTF has provided over a decade of EW and EM T&E capability.

The sub-system test laboratory and chamber have been extensively used during the development and production clearance of the Typhoon and its DASS. For some years the EWTF has also been used for DASS mission data support and training by the four Typhoon partner nation Air Forces. It has also supported the design, development, performance verification and in-service support of a number of UK front line aircraft during that time, e.g. Fig. 20.

In chamber mode, the SUT can be a whole aircraft with installed DAS, a part-platform, e.g. Typhoon wing tip pods (which house DASS sensors) or an un-installed RF EW equipment, radio, data Link system or other RF transmitter/receiver. In laboratory mode, see Section 6.1.2, the SUT is usually RF-stimulated and -measured 'post-antenna', i.e. with no free space radiation.

In addition to the above technical features, there is a comprehensive programme of facility maintenance, planned upgrades and obsolescence management.

7.2 Recent technical developments

The EWTF complex is currently nearing the end of a multi-£M upgrade. The bulk of the upgrade, a complete replacement of the RF threat simulator and ECM RMS, required to support Tranche 2 Typhoon DASS testing, was contracted December 2006. This section describes this and potential future upgrades, focusing on the instrumentation upgrade, see Fig. 21.

7.2.1 EWTF upgrade elements

The main elements of the EWTF upgrade are given here:

- Replacement of major EW T&E instrumentation: The two primary items of EW T&E equipment, RF threat simulator and ECM RMS reached their end-of-11 year specified life in 2008. Increasing obsolescence and failure rates on both equipments in recent years, culminating in the August 2009 death of the RMS, confirmed upgrade timeliness.
  - RF threat simulator replaced by Amherst CEESIM MkN known as 'RFEG-2A' (RF Emitter Generator). CEESIM is the *de facto* standard many-channel RF threat simulator in the UK, with multiple copies at DEWC[10] (UK fixed/rotary wing platform in-service support), multiple copies at BAE Systems (Warton), and others at RAF Coningsby (Typhoon national support capability) and SELEX Galileo (EW equipment testing). This commonality is important, as it increases test repeatability and aids problem investigations across agencies, test locations.
  - RMS replaced with tailored, state-of-the-art version of SMS, 'RMS-2', which is highly common with those recently provided for RAF in-service support of Typhoon and Nimrod MRA4. Has extra capability to enable the EWTF to meet the more stretching DT&E mission.
- Instrumentation time synchronisation system: obsolete system replaced; integral with RMS-2, known as 'TSS'.
- Chamber 'refresh':
  - 11 replacement RF amplifiers (microwave/millimetre wave).
  - Replacement threat site signal switching matrix at all six sites
  - New 30 tonne multi-platform handling equipment for crane
  - Replacement thermal cameras and secure/non-secure intercom
  - Improved fire detection and water deluge system
  - Refurbished turntable; cooling for aircraft radars
- Other upgrades to EWTF complex:
  - Chamber/laboratory/office air conditioning refurbishment, with extra capacity added
  - New, 2nd super-computer for Computational EM Group
  - Replacement EWTF telephone system

These developments will enable BAE Systems to better discharge its contractual responsibilities on Typhoon and provides the capability to meet some of the Section 4 challenges. The potential future upgrades identified in Section 7.3 would substantially improve the upgraded EWTF's capability and enable a step

Figure 20. Selection of aircraft tested in EWTF chamber.

improvement in the EW T&E of UK air platforms, contributing to resolution of all the Table 2 challenges. In turn this would lead to significant time, cost, performance and risk benefits to customers.

7.2.2 The upgrade solution

The RFEG-2A and RMS-2/TSS specifications, 274 pp. in total, were authored by the EWTF Team, including this paper's authors. The specifications captured test requirements from the BAE Systems Typhoon DASS Team and were augmented thus:

- Lessons learned and user suggestions from 12 years of EWTF, Typhoon DASS and MRA4 DASS EW/DAS testing.
- Discussions with and input from DEWC representatives.
- Inputs from international CEESIM users, EW equipment suppliers, e.g. SELEX Galileo, and the supplier, Amherst.

Requirement-underpinning R&D and other investigations were conducted by these authors since 2002, some supported by Amherst. These have led to a number of technical performance and operational improvements, e.g. higher fidelity SUT receive antenna pattern modelling and substantially improved CEESIM power supplies' reliability. Some of this effort is described in Ref. 10.

Figure 21. RFEG-2A (CEESIM) and RMS-2/TSS (SMS/TSS).

Table 8
Instrumentation enhancements and their benefits

ECM response measurement and analysis: RMS-2 compared to original RMS	
Wider receiver bandwidth	80MHz *vs* 10MHz enables better, reduced time/effort capture of jamming waveforms
Improved dynamic range	Greater signal detection range
Improved low sensitivity signal detection	Improved detection at lower signal-to-noise ratio
Event-driven capture	Improved capture of transmitted jamming waveforms, triggered by cues from DAS bus message
RF threat simulation: CEESIM MkN (RFEG-2A) compared to original AMES-II	
Increased quantity and more flexible use of microwave RF channels	AMES-II had sub-banded microwave channels. RFEG-2A has novel configuration in this band: ● All microwave frequency-locked oscillators and high-speed synthesiser channels are wideband. All are fully interchangeable with channels in the other three recently acquired CEESIM MkNs in Typhoon system integration laboratories at Warton, to optimise test capability ● Can be configured to have up to ten high-speed synthesisers, significantly improving complex threat scenario generation capability and fidelity
Enhanced wavefront-to-receive antenna polarisation mismatch modelling	AMES-II only had simple polarisation mismatch modelling CEESIM MkN has full vector modelling of polarisation mismatch effects
Improved calibration and fault diagnostics	CEESIM MkN fault diagnosis capabilities are greater, calibration is more rigorous than AMES-II
Integrated antenna pattern utility	Provides visualisation, interpolation and editing capability not on AMES-II and earlier CEESIMs
Much improved SUT receive antenna modelling capability	AMES-II provided only 512k data points/antenna, limiting environment simulation fidelity. Latest CEESIM MkN models provide 3.1 M data points/antenna, offering useful single and multi-emitter scenario fidelity improvement
Environment Graphical Analysis tool	Allows user to construct emitters/scenarios and run scenarios, in non-real-time. Hosted on CEESIM and stand-alone/networked workstation. Not available on AMES-II
CEESIM – Less RF noise in laboratory and chamber modes of operation	● These authors specified all CEESIMs from that for the Typhoon national support capability (2008) onwards to have a 'pulse off' noise threshold of -105 dBm/MHz. ● Reduces risk of SUT seeing simulator noise as emitters, a previously seen problem ● Feature becomes more important as 'digital' (more sensitive) receivers become commonplace
Less RF noise in chamber mode	RFEG-2A includes a new feature which provides timing control ('skirt times') of RF amplifiers' grids used during chamber tests, to minimise pulse-off noise being transmitted into the chamber and potentially resulting in false emitters being detected by the SUT
Full control, auto-calibration of EWTF chamber's millimetre wave capability	Features not previously available on the AMES-II. RFEG-2A will provide same level of test, calibration and safety control as all other chamber amplifiers

EW T&E instrumentation function and performance enhancements realised through the EWTF upgrade are given, with benefit indication, in Table 8.

Planned and proposed near term upgrades include:

- EWTF Annex: additional test laboratory space + secure storage
- RFEG-2A:
  - Frequency extension for laboratory and chamber use
  - Performance network analyser for faster calibration
- RFEG-2A and RMS-2/TSS: Selected items from the potential future upgrades in section 7.3
- Turntable: improvements to positional accuracy and operation.
- Higher performance replacement of 1st super-computer for Computational EM Group
- Upgrade of closed circuit television system

Where sensible and affordable, 'future-proofing' the EWTF upgrade elements has been effected. It is thus positioned to better support the *Defence Industrial Strategy*'s forward-looking challenge - to provide defence 'equipment that are: fit for the challenge of today; ready for the tasks of tomorrow; capable of building for the future'.

7.3 Potential future EW T&E developments

Technical developments of note to Radar Frequency EW T&E systems are discussed, focusing on those items that will likely lead to step improvements in meeting the Table 2 challenges. Other EW T&E equipments are mentioned. Suggested underpinning research topics are proposed, with the primary target of minimising the number of test iterations required to achieve customer acceptance and the need for expensive and difficult to repeat flight testing.

Table 2 includes a number of self-explanatory developments where the EW T&E community could enable or contribute to challenge solutions. Examples include closer cooperation between key players in the community and networking of UK EW T&E, SE and M&S facilities. These are not discussed further in this section.

7.3.1 Identification of significant developments

These authors have been involved in the development of EW T&E systems for over 25 years and have co-authored the tender and contract specifications for all major RF threat simulators and most ECM RMS acquired by their Division during that time. In developing these specifications they have conducted various studies of function and parametric performance of RF signal simulation and characterisation, and jamming technique measurement and analysis. In his former role as Divisional EW R&D Manager, this

Figure 22. Chameleon II radar target and ECM simulator.
(© EWsT, a Herley Company, 2009)

lead author has instigated, led and conducted various research activities targeting higher quality RF threat emitter simulation for EW T&E use in laboratories and the EWTF. Some investigations and product development activities have been conducted in collaboration with Amherst. Since 2001 these authors have developed and maintained a 'Potential Enhancements' list which has been reviewed, usually with DEWC representatives, during construction of each subsequent threat simulator and ECM RMS specification.

This lead author published a 2007 Position Paper[19] on RF threat simulator technology developments, which described the previous 15 years' developments. An invited presentation to the 3rd CEESIM User Conference followed in June 2009 (Peterborough, UK), entitled 'CEESIM and SMS – Where to Next? – An Industry View of Potentially Worthwhile Developments.' Although focused on the two Amherst products, CEESIM and SMS, as now used extensively in the UK, many potential developments identified are relevant to most T&E equipment of these types.

Development categories investigated were:

- Technical performance.
- LCC – purchase, operation and maintenance.

Table 9 provides an updated and wider view of EW T&E equipment developments from the above presentation and Ref. 7. It covers items considered to offer most benefit with quickest implementation.

Developments are ranked by impact consideration. All are key enablers, underpinning efforts to meet Table 2 challenges. Most are considered near-term implementable, on new units and by retrofit, as required technology either exists or Technology Readiness Levels could be quickly increased once funded. Some are of greater importance to EW T&E in the near future, should the enhanced performance promises of 'digital receivers' be fully realised, cf. Ref. 7.

While specifically aimed at enhancing anechoic chamber and laboratory T&E capability, to enable reduced flight testing, many are also applicable to the use of these equipment types on open air test

Figure 23. Example of RISS hardware.
(© Northrop Grumman Amherst Systems Inc. 2009)

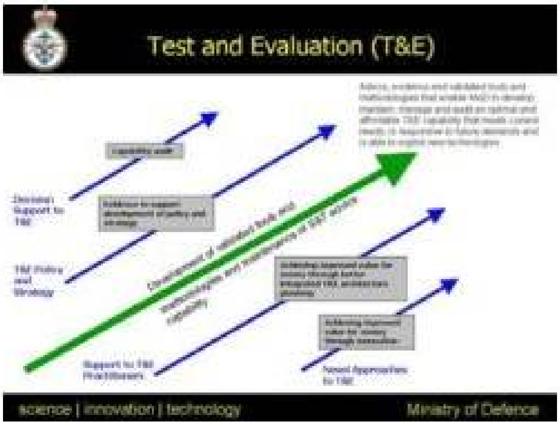

Figure 24. DTP roadmap – test and evaluation.
(© Crown Copyright 2009)

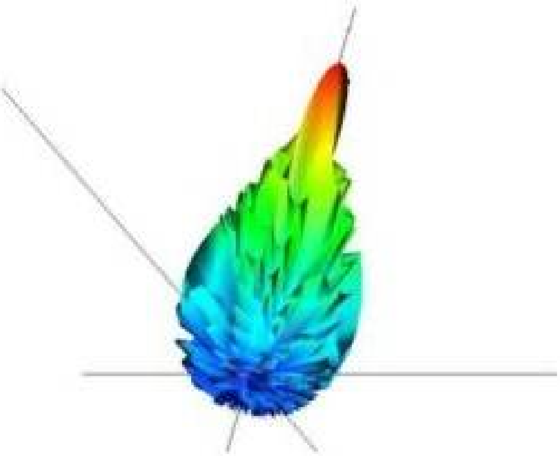

Figure 25. Emitter antenna modelled using CEESIM's Integrated Antenna Pattern utility.
(BAE Systems Image)

sites and flight test and training ranges. EW T&E equipment already 'off the shelf' or near so is not included in the table, e.g.

- Jammer simulation – most threat emitter simulators are, by definition, not high fidelity jammer simulators, for which additional equipment is required, e.g. EWsT's Chameleon II radar target and ECM Simulator, see Fig. 22.
- Amherst's 3rd generation Real-Time IR scene simulator (RISS), see Fig. 23, which is now operational in a number of laboratories and in at least two (US) anechoic chambers.
- Communications, navigation and identification signal simulators, including radar target generators.
- Lasers for laser warner testing.

7.3.2 Underpinning research and other investigations

Further research and other investigations are required to underpin realisation of cost, time and risk benefits of developments described in this paper. To aid prioritisation, proposed activities have been considered against the key challenges of Section 4 and relevant parts of MoD's *Defence Technology Plan* (DTP)[15] and *Defence Research 2009*[16], and for relevance to ongoing UK military aircraft programmes, e.g. Typhoon.

The DTP is UK MoD's cost-balanced list of current R&D priorities. It takes the *Defence Technology Strategy* forward, providing clear direction to the R&D community on investment in defence technology and seeks fresh, innovative thinking. The DTP is set out as high level R&D objectives that are associated to Systems, e.g. aircraft and helicopters. Objectives are to be met via research activities, which are grouped into themes. The relationship of themes and activities within an objective is presented as a roadmap. For example the T&E Roadmap, Fig. 24, appears under the heading of 'Systems, Cross-Cutting' and the air platform survivability roadmap (which is classified, so is not publicly available) appears under 'Systems, Aircraft and Helicopters'.

Table 10 identifies items under the five R&T thrusts from Ref. 16 considered to be most relevant to this paper.

Table 10
R&T thrusts most relevant to EW T&E

THRUST	ITEM
Survivability	Cost-effective survivability options: – Consistent, robust, validated tools – Understanding legacy platform protection – Survivability benefits, networked DAS – Helicopter survivability requirements – DAS open architecture – IR Missile Approach Warner sovereign capability – UK laser sovereign capability – Compact DIRCM, defeat IR-guided threats – Suppression of long range Surface-to-Air Missile threat
Platform	Affordable, effective and persistent air capability: – Understand performance of future UAS – Integration of UAS alongside manned platforms
Agility	Rapid, cost-effective and agile integration of new capability: – Easy porting of legacy software onto new hardware – Open architectures: parallel, reconfigurable computing – Distributed processing – Software emulation – Networked functionality on legacy platforms
Decision Making	– Coordinated and timely effects through improved air decision making: – Mission rehearsal – Integrated sensor and effector network
Human Factors	Human physical and cognitive performance expanded and included in system design: – Aircrew training

Recommended research and other investigations follow, grouped under Table 2 headings. Some warrant 'spend to save' enabling funding by Customers, as the T&E benefits and LCC reductions are likely and worthwhile in overall affordability terms.

<u>Optimisation, development and sustainment of EW T&E facilities</u>

- <u>More operationally realistic threat environments for T&E</u>: Investigate benefits and limitations of generating more operationally realistic and measurable threat environments in anechoic chambers and laboratories. Specifically:
  - Conduct underpinning research to enable the Table 9 developments, enhance problem finding capability and increase Mission Data quality. Initial focus on better representation of real-world threat antenna patterns, cf. Fig. 25, on subtle intra-platform EM effects, cf. section 5.5 of Ref.(10) and on obscuration by own platform features e.g. Fig. 26.
  - Investigate RF threat simulator requirements for high fidelity stimulation of multiple, networked EW SUTs – not just Multi-Platform Emitter Geo-Location, as studied in NATO Industrial Advisory Group Sub-Group 79, but also multi-platform RF jamming with manned and UAS components.
- <u>High performance IR/EO scene simulation for EW T&E</u>: Investigate cost-benefit trades of RISS-type IR/EO scene simulators for UK anechoic chamber and laboratory environment.
- <u>Improved RF threat simulation fidelity</u>: Research RF threat simulation fidelity, probably the key enabler of maximising EW T&E transfer from flight to anechoic chamber and laboratory. The topic is discussed comprehensively in Ref. 10, Section 5 'Simulation Fidelity – the quest for affordable emulation'. Figure 27 highlights the key question – 'How good is enough?' That is, at what point does it become more cost-/time-effective to test fly on a range against the real threat rather than invest further in enhancing ground-based EW T&E capabilities?
- <u>EW T&E problems – root cause analysis</u>: Research EW SUT problems reaching flight and combat. Determine EW T&E facility and process developments to trap these and similar problems earlier in future. Identify recurrence prevention options. NATO RTO's SCI-203 update of Ref. 11 includes effort in this area.

<u>Rapid development, insertion and acceptance of EW improvements</u>

- <u>Future EW systems/upgrades – T&E capability development</u>: Analyse outcomes of NATO and other 'future of EW' studies to postulate future EW upgrades/UORs and thence facility upgrade requirements. Determine implementation lead times and, after likelihood consideration, plan to assure timely readiness for test.
- <u>Mismatches between flight and ground test results</u>: Research mismatches between test/combat flight results and those from

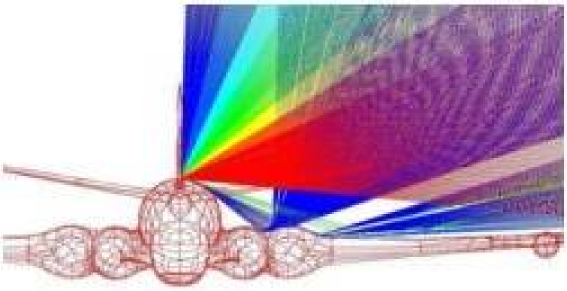

Figure 26. Modelled obscuration effects.

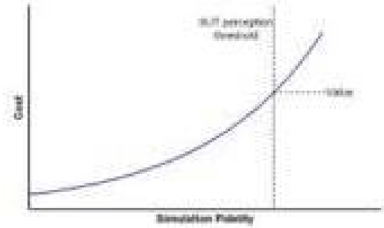

Figure 27. RF simulation fidelity – how good is enough?

Table 9
Worthwhile CEESIM/SMS potential developments

	POTENTIAL EW T&E EQUIPMENT DEVELOPMENTS	IMPACT: Lower LCC	IMPACT: Better T&E	IMPACT: Less Flt Test
	RF THREAT SIMULATORS			
1	**HIGHER FIDELITY OF THREAT EMITTER ANTENNA PATTERNS:** –Current '2-D' elliptical modelled patterns, at 5k data points/antenna, limits complex, dynamic scenarios –Up to 5.5 M data points/antenna could be available for improved modelling of real-world, irregular patterns	N/A	H	H
2	**REAL WORLD THREAT AND OTHER EMITTERS' ANTENNA EFFECTS:** –Real radiation spillover and random polarisation in sidelobes	N/A	H	M
3	**FASTER HIGH-FIDELITY INTRA-PULSE MODULATION (HFIM) SAMPLE RATE:** –<1 ns desired to test 'Digital' and receivers with 'Specific Emitter Identification'-level of capability	N/A	H	H
4	**PLAYBACK OF RECORDED DATA THROUGH CEESIM FOR LABORATORY & CHAMBER TESTING:** –Replay for Pulse Descriptor Word recorded by EW systems from flight testing and combat –Replay of threat emitter data recorded at RF, enabling much higher simulation fidelity	N/A	H	H
5	**AFFORDABLE SIMULATION OF INTRA-PULSE MODULATION FOR TDOA-BASED EW RECEIVERS:** –High-Fidelity Intra-pulse Modulation RF channel per antenna, is technically achievable but unaffordable	M	H	L
6	**INCLUSION OF INTRA-PLATFORM EFFECTS TO BETTER SIMULATE IN-FLIGHT TEST CASE:** –Reflections/refraction on own platform not currently modelled in most simulator types	N/A	H	H
7	**EXTREMELY HIGH MODULATION RATIO AND LOWER NOISE SOURCES/COMPONENTS:** –Entire modulation chain affected – for increased sensitivity 'Digital Receivers' –Cleaner representation of Low Probability of Intercept RF signals	N/A	M	M
8	**IMPROVED USER INTERFACE TO EASE EMITTER CONSTRUCTION & SCENARIO VISUALISATION:** –Sub-optimal current interface problematic. 2009 launch of much improved, retro-fittable User Interface	L	H	M
9	**IMPROVED MODELLING OF EW RECEIVER ANTENNAS:** –Simulators generally use 'Calculated Data' antenna model type, each only having a single polarisation –'Measured data' model type higher quality, but requires detailed antenna performance measurements	N/A	M	M
	ECM RESPONSE MEASUREMENT SYSTEM			
1	**IMPROVED DYNAMIC RANGE TO BETTER CATER FOR MODERN ECM TECHNIQUES** –Current technology limitations constrain some areas of performance	N/A	M	M
2	**IMPROVED MEASUREMENT ACCURACY:** –Use of better digitisers (speed and Effective Number Of Bits)	N/A	M	L
3	**AUTOMATIC ECM TECHNIQUE ANALYSIS/IDENTIFICATION:** –Faster testing, especially in the anechoic chamber environment	N/A	M	N/A
	BOTH THREAT SIMULATORS AND ECM RESPONSE MEASUREMENT SYSTEMS			
1	**INCREASED COMPONENT, SYSTEMS RELIABILITY & REDUCED SPARES** –Highly complex RF test equipment requires very expensive spares pack to guarantee availability for test	H	N/A	N/A
2	**REDUCED ENERGY CONSUMPTION, HEAT LOAD:** –Most is powered up 24/7/365. Initial estimate electricity usage >£200k p.a. for UK EW T&E equipment	H	N/A	N/A

laboratory/chamber tests. Develop understanding of problematic mismatch cardinal drivers. Identify EW T&E developments, beyond those in this paper, to deliver mismatch insignificance.

- Efficiency and cost-effectiveness of UK EW T&E facilities:
  - Investigate cost-effectiveness and shortfalls of the EW T&E process, to enable improved efficiency and effectiveness of performance verification and system acceptance. Include consideration of T&E lessons learned, e.g. Ref. 17.
  - Research fusion of data from multiple domains (simulation models, laboratory and flight) as a contributor to cost-effective performance evaluation.
- Transfer of EW testing from flight toward M&S: Determine practical boundaries on EW testing transfer from flight test toward validated M&S. Investigate factors that predominate and identify 'big hitter' and 'quick win' improvement items.
- Synthetic Environments' benefit to EW T&E: Explore SE benefits to EW T&E, focusing on acceptance process use, visualisation of RF scenarios and EW development risk reduction. Progress best use of T&E facilities to support experiments and acquisition, as indicated in Ref. 18, an overview of major drivers and way ahead on UK defence simulation.
- Installed performance modelling of EW antennas: Research improvements for EW antenna modelling, to:
  - Enhance SUT design and de-risk RF interoperability candidate solutions, especially for UAS.
  - Determine incident pulse shape degradation effects, with emphasis on EW receiver and RF threat simulator performance impact, when using combinational antenna types and measurement techniques to determine high grade threat location accuracy and robust identification.

Reduced cost and environmental impact of EW T&E and facilities

- 'Green' EW T&E: Investigate, in conjunction with suppliers, more energy-efficient EW T&E. Explore trades between electricity usage, heat loads, reliability reduction and required availability for testing. Research enabling technologies.
- EW T&E equipment reliability improvements: Research technologies and methods to improve least reliable components, to enable reduction of expensive spares packs currently required to assure specified availability for testing. Of particular relevance to CEESIM and SMS, where many units will be in use across UK MoD and Industry over the next 25-30 years.

8.0 CONCLUSIONS

Conclusions are stated and recommendations made. All target early realisation of enhanced capabilities and processes, to optimise EW development programme cost, time and risk.

- UK MoD and NATO recognise EW systems as key to platform and aircrew survivability and mission success. Changing threat scenarios, towards asymmetric warfare, give further emphasis.
- UK and MoD strategies dictate retention of UK sovereign capability to research, design, manufacture, programme, supply, integrate, test and evaluate and optimise all areas of EW systems.
- EW T&E challenges are identified from UK's *Defence Industrial Strategy* and UK MoD's *Defence Technology Strategy*, Plan and T&E Strategy. These challenges are stressing for manned platforms and some, e.g. RF interoperability, are more complex on UAS. It is considered that UAS development programmes would particularly benefit from developments described herein.
- Areas are identified where the EW T&E community could enable or contribute to challenge solutions. Some areas identified require relatively simple implementation actions, whereas others require research, other investigations and development of facilities.
- EW systems' digitisation is driving significantly better performance that will require enhanced EW T&E facilities. Some required enhancements are, or are nearly off-the-shelf, but a number require research and product development.
- Technical developments from the recent multi-£M upgrade to BAE Systems' aircraft-sized anechoic chamber EW Test Facility are described. This upgrade includes state-of-the-art RF threat simulation and ECM response measurement and analysis systems, and emphasises its position as a national EW T&E asset.
- Sustainment of UK EW T&E capabilities and further development as proposed herein will yield significant benefits:
  - Fewer expensive EW flight tests and operational flight trials.
  - Fewer UK aircraft EW trials at overseas facilities and ranges.
  - Lower cost, less risky and shorter timescale programmes for rapid insertion of EW system enhancements.
  - Higher quality EW Mission Data validation, at reduced cost.

  The EWTF is believed to have a key role in benefits' realisation.
- A range of challenge solution options and enabling potential future developments are suggested:
  - Significant, near-term improvements to RF threat simulators and ECM response measurement and analysis systems.
  - Underpinning research and other investigations, including exploration of optimum balance between traditional EW T&E and Modelling and Simulation and Synthetic Environments.
- The cardinal benefit driver is improved RF threat simulation fidelity – the ability to produce near-perfect replica RF waveforms to those produced by threat weapon system radars. Technology progress over the past 15 years and product developments known to be in progress suggest that this 'emulation' goal may indeed be viable.
- It is crucial to maintain the UK industrial EW skill base if the potential benefits in this paper are to be realised. *The Defence Industrial Strategy* recognises this as a challenge. It is thought resolution lies within Long Term Partnering Agreements that are still under consideration by MoD and Industry.
- The desired significant reduction in EW systems' development time, cost and risk is likely with the developments in this paper.

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This paper is dedicated to the memory of Darren Tolsma and three other Amherst Systems Inc. staff who died February 2009 in the Buffalo flight 3407 crash. Darren had worked with this paper's lead author on threat simulator developments in recent years – his cheerfulness and enthusiasm for the EW T&E mission is missed.

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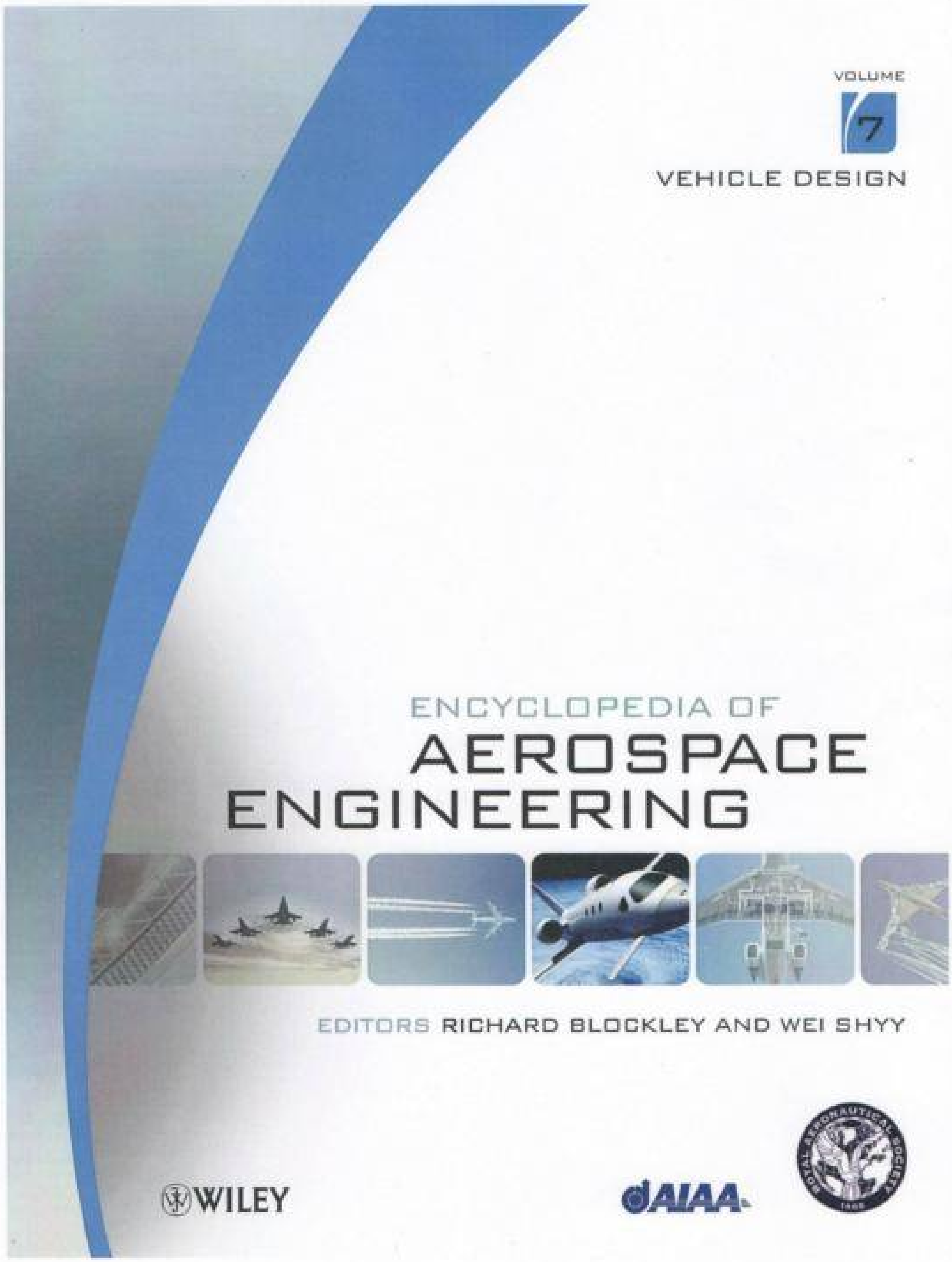

Electronic Warfare and Defensive Aids Systems Design and Development

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1 INTRODUCTION

This chapter describes systems Design and Development (D&D) of airborne Electronic Warfare (EW) systems, in particular the self-protection Defensive Aids Systems (DAS) that are essential to military aircraft and aircrew survival when going "in harm's way." Whilst much of this chapter is equally applicable to the individual components of EW systems and DAS[1], it primarily focuses on platform-level aspects of the latter. For the remainder of this chapter the term "DAS," unless stated otherwise, is thus considered interchangeable with "EW."

EW definitions are provided, EW's contribution to platform and aircrew survivability is outlined, and EW systems are described. The route from military user need, through defense procurement agency ("customer") requirements expression, to DAS and EW equipment specification is explained. System acceptance philosophy and methods are described, and the EW test and evaluation (T&E) process outlined. T&E capabilities required to support D&D, performance verification and customer acceptance into military service are described.

This chapter is written from the perspective of a military air/sea/land platform Prime Contractor[2] (PC) and systems integrator. It provides a UK view and, whilst national variations are known to exist, the processes described are broadly general and T&E facilities similar.

Caveats:

Many aspects of EW are nationally sensitive and some are highly classified. Certain parts of this chapter are thus less detailed than might otherwise be the case. In particular:

- Directed Energy Weapons[3] (DEW), besides Directed Infrared Countermeasures (DIRCM), are excluded.
- Emitter databases that are essential to correct operation of EW systems and associated T&E equipment are not discussed. For the interested reader, Howe (2009) provides an unclassified view of this topic.

Encyclopedia of Aerospace Engineering.
Edited by Richard Blockley and Wei Shyy

2 ELECTRONIC WARFARE SYSTEMS

EW definitions are provided and the importance of EW to aircraft and aircrew survivability is indicated. EW system types are also described, with focus on those for the DAS subset of EW, which are fitted to most military aircraft, whether fixed wing or rotary wing (helicopter).

2.1 EW and survivability

Table 1 provides internationally accepted definitions of EW and its components EW Support (ES), Electronic Attack (EA), and Electronic Protection (EP), also called Electronic Defense (ED) in the UK.

Table 2 shows how EW contributes to the air platform combat survivability equation, whose components are threat avoidance, attack evasion, threat elimination, and damage tolerance. Optimized survivability arises from achieving the best balance of these components. Damage tolerance, also known as platform vulnerability, is excluded from Table 2 as EW does not contribute – damage tolerance is the ability of the airframe and systems to sustain weapon fragment damage and continue the mission or return to base for repair (see Design Aspects of Aircraft Vulnerability).

The increased survivability afforded by EW systems equates directly to increased probability of mission success and aircrew and aircraft safe return to base.

2.2 EW systems description

EW systems are a super-set of the generalized DAS shown in Figure 1. Other EW components not usually part of DAS, and thus which are not discussed further in this chapter, are

- Electronic Intelligence (ELINT) receivers, although shown in Figure 1 to indicate how in recent years the

Table 1. EW definitions.

EW – Any military action involving use of electromagnetic and directed energy (EM, DE) to control and protect the own usage of the EM spectrum or to attack an adversary and deny his access.
ES – That division of EW involving actions tasked by, or under direct control of, an operational commander to search for, intercept, identify, and locate or localize sources of intentional and unintentional radiated EM energy for the purpose of immediate threat recognition, targeting, planning and conduct of future operations.
EA – That division of EW involving the use of EM energy, DE, or antiradiation weapons to attack personnel, facilities or equipment with the intent of *degrading*, *neutralizing*, or *destroying* enemy combat capability.
EP – Actions taken to *protect* personnel, facilities and equipment *from any effects* of friendly or enemy employment of EW that degrade, neutralize, or destroy friendly combat capability.

Table 2. EW contribution to survivability.

	Survivability component		
EW	Threat avoidance	Attack evasion	Threat elimination
ES	Own & networked ESM/ELINT/COMINT, Emitter Locator System & RADAR/Missile/Laser Warners to: • Optimize situation awareness • Inform preflight mission planning • Enable in-flight re-routing • Feed friendly network-enabled capability	• Cue own RF/EO/IR countermeasures • Cue support ECM – Stand-off – Escort – Close-in (e.g., UAV)	• Cue own weapons and countermeasures • Cue support jamming • Vector friendly weapon systems onto threat
EA	Deception and saturation jamming • Deny threat sensors' knowledge of own platform position	RF/EO/IR Jamming & DE Attack: • Deny opponent's targeting and firing solutions • Decoy incoming missile or fire	• Stand-off/-in, self-protect & escort RF jammers • CHAFF/Flares • EO/IR jammers • Antiradiation missiles • DE attack
EP	Own EW sensors Antijam (counter-countermeasure) capability provides own platform with continued passive Threats' detection, identification and localization		

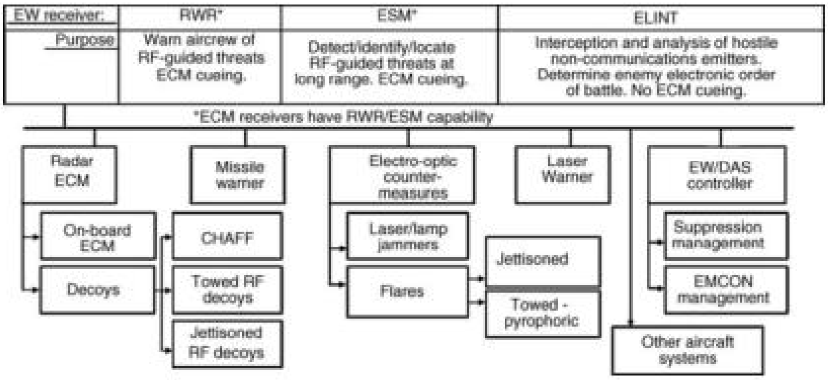

Figure 1. Generalized DAS block diagram.

technical performance boundary between RWR, ESM, and ELINT has become blurred.

- Stand-off and escort jammer pods.
- Antiradiation Missiles.
- Communications intelligence receivers.
- Communications frequency ESM and jammers.
- Jammers of Navigation/Global Positioning Systems and Data Links.

A platform's DAS is a function of platform type, role, mission, and operational theatre, so not all platforms will have all components and required component capabilities can vary. For example a different DAS is likely for:

- Air-to-air defense fighter operating over hostile territory.
- Low-level bomber attacking heavily defended targets.
- Air-to-air refueling tanker, which generally remains in "safe," or at least "protected" air space.

Many DAS configurations exist, usually falling into one of the three primary installation types:

- *Fully integrated:* Usually only possible when designed as part of the platform during original development. Figure 2 indicates such a DAS, that on the Eurofighter Typhoon.
- *Federated/partially integrated:* Frequently the case where function and/or performance of original DAS component is enhanced and overall performance improved via better integration with other DAS components and the platform's displays and controls subsystem.
- *Stand-alone DAS:* Often a podded solution, this is a way to introduce a new, replacement, or upgraded DAS. Relatively simple to integrate with the platform. When operational requirements do not mandate DAS for every mission, can be cost-effective. Such "role fit" DAS are especially attractive for Unmanned Air Systems (UAS)[4].

3 FROM SYSTEM REQUIREMENTS TO EQUIPMENT SPECIFICATION

Conversion of customer's requirements into system, subsystem, and equipment specifications is explained. Whilst showing in some detail the process for EW equipments and DAS for UK-purchased platforms, this chapter is not a topic exposition. The general process for aircraft systems is covered elsewhere, for example Moir and Seabridge (2008) and its references.

3.1 Levels of requirement complexity

Requirement statements vary dependent on a number of things, for example, contracting method (individual EW equipment or whole DAS), and customer's wishes and level of specialist EW knowledge. They are expressed in terms of what function and performance is required of a platform, system, subsystem, or equipment. "Function" is what is required to be done, for example ESM shall measure frequency, "Performance" is how well it must be done, for example ESM shall measure frequency to an accuracy of 10 MHz, with a resolution of 5 MHz.

Requirements lie in the range below:

- *Simplest requirement:* Fit single, customer-mandated EW equipment on customer-defined platform. Not uncommon, especially for Urgent Operational Requirements

Figure 2. DAS equipment locations on Typhoon. BAE Systems © 2009.

(UORs) and export customers. Usually the least technically complex task. Least risky for Industry, as the equipment's function and performance, when integrated to the platform, is constrained by the mandate.

- *Top level requirement:* Provide adequate survivability for a given platform against threats to be encountered in specified geographical region(s), irrespective of time of day, month, and weather conditions. Rarely contracted on Industry at such a high level of requirement. Likely to become common as Defense Ministries move toward Integrated Survivability specification of platforms (UK Ministry of Defence, 2006). This is the technically most complex case and, for Industry, riskiest.
- *Most common requirement:* This is where:
  - The customer specifies individual DAS equipment types or states "solution shall (or is expected to) include list of DAS equipment types, for example Flares, Chaff, ESM, On-board RF Electronic Countermeasures (ECM) and Towed Radar Decoy."
  - Threat scenarios are usually defined by the customer and his Technical Advisors, for example Defense Science and Technology Laboratory (Dstl) in the U.K., and provided to the PC and thence to the DAS/EW equipment suppliers.
  - PC is responsible for DAS configuration and function and performance specification of its EW equipments. The PC has the freedom to choose which manufacturer's DAS or EW equipments are to be fitted to the platform, subject to meeting any customer-specified function and parametric performance, for example ESM frequency range "*x* to *y* GHz."

3.2 Origin of requirements

The UK start point for a platform or upgrade requirement is the military user's top-level Single Statement of Need. This is expressed in detail in the two-part User Requirement Document (URD). Part 1 provides a General Description and Part 2 defines prioritized Key User Requirements. The URD is part of the Initial Gate Business Case and enables development of the System Requirement Document (SRD). The SRD:

- Defines the characteristics MoD require and expect from an equipment-based solution to the URD and is part of the Main Gate Business Case.
- Drives the Statement of Requirement sent to Industry, which results in an equipment contract specification.
- Can also lead to a MoD-generated Equipment Contract Specification, to enable procurement. The Statement of Requirement and Specification, whether MoD- or Industry-produced, are measured against the SRD.

- Is also required for the special case of requirements arising from imminent or ongoing operations, the UORs.

URD, UOR, and SRD are solution-independent requirements statements. U.K. MoD's Acquisition Operating Framework (UK Ministry of Defence, 2009) provides a full explanation of the above. SRD development is informed by Operational Analyses, from which Concepts of Operation are developed. These analyses consider the possible range of mixes for Avoid, Evade, Counter, and Sustain for the platform's role, mission, and operational theatres. Other factors initially considered are operational- and cost-effectiveness and technology availability.

Example EW-related questions and trade-offs are:

- In what RF, Electro-Optic (EO) and IR/UV threat scenarios is the DAS required to provide survivability, to underpin what level of mission success probability?
- Does high quality threat emitter parametric data, Electronic Order of Battle and information on own/opponent's tactics exist or how and by whom will this be defined or estimated?
- Is a fully capable self-protect RF ECM necessary, or do Stand-Off, Escort and UAS-based Stand-In Jammers have a role to play in force package survivability trade-offs?
- What is the trade space for survivability adequacy versus affordability versus technical/cost/schedule risk?
- What are the trade-offs between various factors affecting the level of DAS complexity and how are they related? Examples include Radar Cross Section (RCS) and IR Signature versus RF and IR ECM capability.

The reader interested in typical function and performance characteristics of DAS component equipments is referred to Adamy (2001, 2004) and their references.

As a closing note it is important to recognize that, through the typical 20+ year operational life of an EW system, its requirements will evolve way beyond those originally specified. New and modified threats, new operational environments, and elevated user performance expectations add a complex dimension to requirements management.

3.3 Route from requirements through specification to contract award

3.3.1 Requirements decomposition

Industry responds to a customer's requirements by decomposing them into tender specifications and adjunct Interface Control Documents (ICDs), against which a commercial offer is made. Dependent on requirement scope, whether for complete platform, a DAS or an EW equipment, the PC conducts some or all of the following, with DAS/EW equipment suppliers' support.

- Platform Request For Proposal conversion into a Weapon System requirement and thence into subordinate requirements for Air Vehicle, Avionic Systems, and Non-avionic Systems.
- Requirements decomposition, using tools like DOORS[5], to a level suitable for conversion into unambiguous specification statements, with contractual qualifiers, for example "shall," "should," and "must."
- Generation of:
  - System and Subsystem Specification(s) and ICDs
  - Equipment Specifications and ICDs. Note: Hardware and software system and component specifications are not normally produced until the PC is on contract.

Two main approaches are used to ensure a full set of requirements are captured and adequately expressed – "Top Down" and "Bottom Up." A mix of the methods is usual, dependent on whether the platform, system, subsystem, or equipment to be developed has any pre-existing component. For example a "Top Down" approach would be used if the required DAS did not exist and had to be developed from the beginning. A "Bottom Up" approach would be used where a DAS was required where four out of six equipments pre-existed on the platform or were commercially available, thus constraining what could be achieved at DAS level. Chapter 11 *System Design and Development* of Moir and Seabridge (2008) contains further information.

3.3.2 Assessments and trade-offs

For appropriately balanced, capable and affordable DAS solutions, Industry conducts a range of investigations, including:

- technology evaluation;
- cost-benefit trades;
- reliability, maintainability, and testability assessments;
- technical, schedule, and cost risk analyses.

In particular, for DAS areas where technology development is required to meet a specification requirement, particular consideration is made of Technology Readiness Levels (TRLs), see Figure 3, which are based on the original NASA TRL Definitions by Sadin, Povinelli and Rosen (1989). TRLs enable an assessment of capability insertion dates. A good insight into this aspect can be gained by reference to the

TRL	Readiness level
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and 'flight qualified' through test and demonstration (ground or flight)
9	Actual system 'flight proven' through successful mission operations
	Progression of levels
1-2	Basic technology research
2-3	Research to prove feasibility
3-5	Technology development
5-6	Technology demonstration
6-8	System/subsystem development
8-9	System test, launch and operations

Figure 3. Technology readiness levels. (With acknowledgment to NASA.) Reproduced from Sadin *et al.* (1989) © Elsevier.

Generic Aircraft DAS Technology Tree Figure 2 of Annex B of UK Ministry of Defence (2006), which gives a breakdown of DAS and its subsystem functions, equipments and underpinning technologies, and shows the then (2006) view of innovation and development contributions made by various players. It is noted that the *Technology Trees* (UK Ministry of Defence, 2006) also highlight the integral role and contribution of academia to research programs underpinning technology innovation in support of military capability development.

The importance of using Modeling and Simulation (M&S) and Synthetic Environment (SE) tools as early as possible in the D&D process cannot be overstated. These aid specification robustness by simulating operational use of the system being specified. An example is the Environment Generation and Analysis tool, part of the CEESIM[6] RF threat simulator, which is widely used in EW T&E by Industry and military agencies. Time-line RF emitter scenarios can be generated that can be used to better specify EW receiver systems and provide an agreed set of verification test scenarios to support system acceptance.

3.3.3 DAS installation issues and trades

In the process of developing the DAS specification and individual EW equipment specifications there are a number of platform installation issues that have to be addressed before arriving at a robust installed performance solution.

Some are relatively trivial and tend not to cause many problems during the D&D, performance verification, and customer acceptance phases. Others, for example RF antenna placement, can be costly and time-consuming to resolve if a fully robust design scheme is not achieved precontract.

Some of the more notable installation issues are listed here.

- Platform environment: temperature and altitude ranges, vibrations levels, and so on. These restrict placement opportunities for some EW equipments, for example IR/UV Missile Warners.
- Structural strength at proposed platform attachment points is a placement restrictor, for example the structure must be capable of withstanding the appreciable forces of simultaneous flare ejections from flare/chaff dispensers.
- Restrictions on required fields of view of:
  - Optical sensors and effectors, caused by obscuration by parts of own airframe. Relevant to IR/UV Missile Warners, Laser Warners, and DIRCM systems.
  - RF sensors and effectors, caused by obscuration by parts of own airframe. Relevant to RWR, ESM, ELINT, and on-board and towed RF jammers. Figure 4 indicates this issue for RF transmit antenna location.

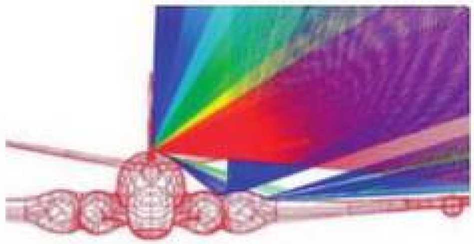

Figure 4. Modeled obscuration effects. BAE Systems © 2008–2009.

- Inbound and outbound EM emissions' multipath around own platform, across the EM spectrum. Whilst generally less of a problem for EO/IR/UV EW systems, these effects can be very problematic for RF EW systems when complicated by the obscuration topic above.

3.3.4 Installed versus uninstalled performance

An important installation consideration not covered in the previous subsection is the subtle difference between "uninstalled" performance, that is not fitted to the host platform, and "installed" performance, which has been the root cause of many RF and EW system problems worldwide.

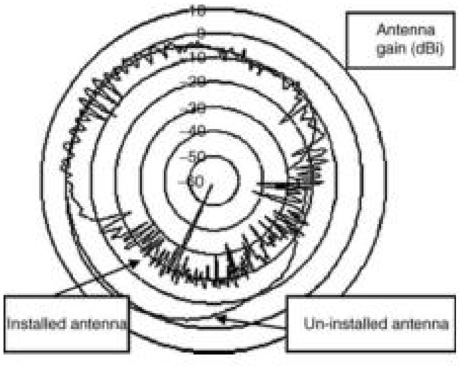

Figure 5. Uninstalled versus installed antenna performance. BAE Systems © 2009.

For many avionic systems without an interface outside the platform, their performance in a laboratory or on a ground test rig is no different to that when in flight and combat. For some systems, or rather for their sensors, there is significant performance difference between the uninstalled and installed cases. One of the best examples is that of RF antennas (see Installed Antenna Performance Design and Verification). Figure 5 exemplifies the difference in antenna gain versus angle off boresight for a RF antenna in isolation versus that when installed in the aircraft. Failure to adequately optimize antenna placement at the outset and ensure the EW receiver hardware and processing can handle these differences can lead to significant problems in achieving customer-required, platform-level performance. Worse still, operational restrictions on the EW system and platform can result, with adverse impact on survivability.

Fortunately, computational power increases and improved codes over the last decade have led to Computational Electromagnetics (CEM) capabilities that can significantly aid design and performance optimization for transmit and receive RF and EW sensor and effector placement. Ongoing developments are expanding whole-aircraft CEM applicability from the relatively mature sub-1 GHz region through to the highest EW frequencies. The use of such design optimization and problem investigation tools have significant benefits to offer customer, PC and EW equipment supplier alike, and have applicability throughout the EW life cycle.

3.3.5 From tender to contract specifications

The Industry considerations outlined above culminate in tender specifications and ICDs, part of a costed proposal for a platform DAS fit and its implementation, integration, and installed performance verification.

Defense procurement agencies take Industry proposals and input them into Balance of Investment models. For example UK MoD's Combined Operational Effectiveness Investment Appraisal process (Great Britain. Ministry of Defence, 2009) evaluates Industry proposals and solution options generated by their technical advisers. This allows the Balance to be determined and informs solution selection.

Once selection has taken place, the customer, PC and DAS equipment suppliers work to arrive at "Contract" versions of the specifications and ICDs. This usually involves further requirements decomposition, predominantly on the PC-DAS supplier interface, with careful attention to "nonattributable" or "nonderived" requirements, that is, those not resulting from the above decomposition. These are usually baseline knowledge aspects in the PC and/or DAS supplier; ones that the customer is reasonably justified in not having to explicitly state in his bid requirements.

3.3.6 Benefit of joint customer-industry working

Over the last three decades many of the activities in Section 3 have been partitioned between defense ministries and their technical advisors, PCs, platform providers, systems integrators, and multiple DAS/EW equipment suppliers. Inevitably, this led to a number of problems and risk impacts, some severe. Some time ago defense ministries and industry jointly recognized the potential benefits of closer working. It is now usual for most of the relevant activities in this section to be conducted in a joint customer–Industry "Integrated Project Team" ("Project Team" in the UK) working environment, which is conducive to reduction of requirement and specification ambiguities that were often the root cause of difficulties seen previously.

The greater involvement of the military end user and their specialists in the requirements decomposition and specification process for EW equipments has increased quality and lowered program risk in recent years.

There is also now a wider recognition that *Fit For Purpose* does not mean, as was historically the case, *Meets the specification*. The combination of specifications, ICDs, and an associated *Capability and Limitations'* document provides a clear view of *what is* and, as important, *what is not* being provided under a contract. This enables proactive and early resolution of any items that might not be acceptable to the customer. Customer and military end-user agreement to this latter document provides a consistent, all-stakeholder definition of *Fit For Purpose*.

4 SYSTEM ACCEPTANCE

Methods used to achieve UK customer acceptance of EW systems are described. These are similar to those used elsewhere, for example USA and Australia. Methods include EW systems testing in the laboratory, in the anechoic chamber, on open air ground test sites and *via* flight test on specialist ranges. An EW T&E process overview is also provided.

4.1 Acceptance philosophy

Acceptance of defense products by UK MoD is well defined and is comprehensively described in UK Ministry of Defence (2009) under *Requirements and Acceptance*. The set of requirements and acceptance products include URD, SRD, Integrated Test, Evaluation and Acceptance (ITEA) Plan, and Verification and Validation (V&V) Requirements Matrix (VVRM).

V&V is defined elsewhere, for example Section 5.1 of Pywell (2007). Verification is PC-conducted, supported by equipment suppliers, and Validation is conducted by military end users. Verification seeks to confirm platform, systems, and equipments meet their specifications, as derived from the SRD. When augmented by Certification, which includes independent assessment of safety evidence (usually without further testing), this leads to Release To Service and acceptance off contract. Validation is the process by which the user evaluates the delivered solution's fidelity against the URD and assesses fitness for purpose, leading to Operational Readiness. Although views differ on terminology internationally and interagency, Verification in the UK comprises:

- Equipment performance qualification against specification, usually conducted by equipment supplier.
- Subsystem performance verification by the supplier or PC, dependent on contracting arrangements.
- PC verification of system-/platform-level performance.

Within UK final Verification prior to customer acceptance is usually all conducted by the PC, with equipment supplier support during final acceptance testing. Final Certification, usually consisting of a Statement of Design and Declaration of Design and Performance, is also done by the PC and provided to the customer, to satisfy national and destination country certification requirements.

4.2 Acceptance types and methods

Industry elements of the VVRM are usually embedded in equipment contract specifications as a Specification Verification Matrix, also called Verification Cross-Reference Matrix/Index. They can also appear separately – still in line with ITEA requirements – in Verification Test Methodology Documents. These describe who will verify each specification element, how (what verification type and method) and with what T&E facilities. Construction of the VVRM is also an important specification check – the question *Is this requirement testable?* must be answered.

Key aspects are that:

- Customer requirements each map to specification item(s).
- An item is assigned one or more acceptance method and type by which verification can be achieved (see Table 3).

T&E is subdivided into two categories. National definitions differ but these are generally understood:

- Developmental T&E (DT&E) covers development and gathering of verification evidence. The PC (or EW equipment supplier or DAS supplier, dependent on contracting arrangement) is responsible for this testing.
- Operational T&E (OT&E) covers operational evaluation, including tactics development, once the DAS is accepted off contract. This is usually flight trials by the military end user, often with PC and DAS supplier support.

Table 3. Verification types and methods.

Type	Method
Inspection	• Physical inspection, visual verification • Document review • Read-across by analogy, where prior evidence alone is used to fulfill a requirement
Analysis	• M&S, for example mathematical, statistical, physical • Read-across by evaluation, where prior evidence is used to partly fulfill a requirement • Technical evaluation of equations, charts, reduced, and/or representative data
Test	• Laboratory – software test, rig test (by supplier), rig test (by PC) • Anechoic chamber (specialist equipment) • Aircraft ground test, for example EM Compatibility and Interference (EMC/EMI) • Flight test (local or dedicated range)
Demonstration	Un-instrumented rig or aircraft test where requirement is met by observation alone

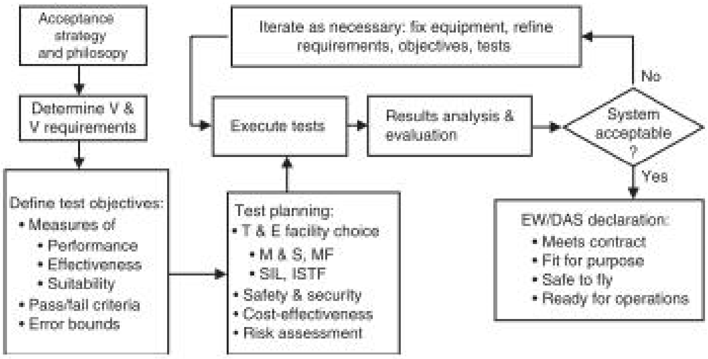

Figure 6. Top-level view of EW T&E process.

4.3 EW T&E process

Whilst there does not currently exist a universally accepted EW T&E process, two related documents suffice to provide a good view of what such a standard process might include. These are US Department of Defense (1995), which is being updated, and North Atlantic Treaty Organization (2000), whose update is due end-2011. Both cover techniques, facilities, and goals of EW systems' T&E.

Figure 6 gives a top-level view of the EW T&E process. Both documents highlight the benefits to be had from optimizing the balance of M&S (T&E without the System Under Test (SUT)), ground testing (laboratory, chamber and open air site) and flight testing on Open Air Ranges (OAR).

As for general systems development, the value of "learning from experience" cannot be over-emphasized and the reader is encouraged to benefit by not repeating preventable problems in the EW D&D and T&E processes. Such problem-prevention knowledge is becoming more widely available (e.g., Stadler, 2007; North Atlantic Treaty Organization, 2000).

5 EW TEST AND EVALUATION CAPABILITIES

T&E capabilities required to support EW system design, development, and subsequent customer acceptance are described. T&E capabilities are defined thus: *A Test and Evaluation (T&E) capability is a combination of facilities, equipment, people, skills and methods, which enable the demonstration, measurement and analysis of the performance of a system and the assessment of the results*. (UK Defence White Paper, 2005).

Facilities and equipment are described with examples. The range of facilities is depicted in Figure 6. A nonexhaustive list of strengths and limitations, with further information for the interested reader, is given in US Department of Defense (1995), North Atlantic Treaty Organization (2000), and Pywell and Midgley-Davies (2009).

5.1 Modeling and simulation

M&S is a crucial element of EW D&D. It is increasingly important as the defense community seeks to minimize cost, time, and risk associated with EW development and upgrade programs. Adamy (2006) provides a useful introduction to the topic of EW M&S for the interested reader.

M&S is employed alongside SE throughout the EW D&D process. M&S and SE have subtly different meanings across nations and agencies, with the terms sometimes used interchangeably. It is generally accepted that both have much value to add in pursuit of the above goals.

For this chapter the definitions in DoD 5000.59-M, *DoD Modeling and Simulation (M&S) Glossary*, as referenced in US Department of Defense (2007), are used:

- M&S: *The use of models, including emulators, prototypes, simulators, and stimulators, either statically or over time, to develop data as a basis for making managerial or technical decisions. The terms "modeling" and "simulation" are often used interchangeably.*

- SE: *Internetted simulations that represent activities at a high level of realism from simulations of theaters of war to factories and manufacturing processes. These environments may be created within a single computer or a vast distributed network connected by local and wide area networks and augmented by super-realistic special effects and accurate behavioral models. They allow visualization of and immersion into the environment being simulated.*

EW M&S is used to:

- Demonstrate system performance for elements that are either too complex or too expensive to verify by testing.
- Where test repeatability is difficult or where tests would yield unacceptable error bounds.
- To supplement testing by interpolation between sparse data points or to extrapolate from measured data.
- Prove design concepts prior to final testing.

Notable issues with EW M&S are:

- Simulation/emulation fidelity[7] and model validation, that is, how faithfully they represent real threats and EW equipments and their performance.
- Modeling of EW antennas, systems, and intraplatform cabling is not currently sufficiently robust to maximize contribution to the EW systems' acceptance process.

One area of M&S showing great promise for EW D&D is CEM. Modern computing power and innovative codes offer useful design optimization and risk reduction for RF antenna installations on platforms (see Installed Antenna Performance Design and Verification). CEM can aid problem prevention and focus sub- and full-scale testing in anechoic chambers and similar facilities. Where problems exist with EW sensors and other RF systems, CEM can aid cost-effective resolution.

Whilst M&S offers increasing benefit to EW D&D, it is considered unlikely that systems will ever be fully cleared by M&S alone, that is, without some residual element of SUT ground test and flight trials.

5.2 System integration laboratories

Systems Integration Laboratories (SIL) are also called Subsystem Integration and Avionic Integration Laboratories. Typical DAS rigs fall into both SIL and Hardware-In-The-Loop (HITL) facility category (the next subsection). Figure 7 shows EW equipment on a typical avionic integration rig.

Testing performed at subsystem level utilizes DAS equipments in a laboratory environment on a 'spread bench,' with all other aircraft data supplied *via* simulations generated by an external control computer, which also serves as master test controller and provides non-RF data acquisition and analysis. Once the DAS has reached suitable maturity it is integrated by the PC with other subsystems, for example Displays and Controls, on an avionic integration rig. System-level performance verification testing is conducted using the EW equipments once integrated with the other real aircraft equipment.

Figure 7. EW equipment on avionics integration rig. BAE Systems © 2009.

Figure 8. RF threat simulator and ECM response measurement system. Label 1: RF threat simulator; Label 2: ECM response measurement system. BAE Systems © 2009.

EW receiver stimulation is affected by threat simulators such as the CEESIM. Spectrum, pulse domain, and other analyzers or an ECM response measurement system, for example Amherst's Signal Measurement System (SMS), are used to capture, record, and analyze RF responses from the DAS's ECM element. Figure 8 shows CEESIM and SMS.

In "laboratory" mode, the SUT is usually RF-stimulated and RF-measured "post-antenna," that is, with no free-space radiation. Integration rigs are continually utilized throughout the platform's life to prove software and hardware changes and to retest system fixes prior to release to the aircraft.

5.3 Hardware-in-the-loop facilities

Although subsystem and avionic integration rigs include, by definition, real avionics hardware in the loop, generally understood HITL facilities are secure (usually screened or anechoic) indoor facilities that enable uninstalled testing of EW techniques against simulation of threats or real threat hardware. Whereas subsystem and avionic integration rigs generally do open-loop EW testing, HITL facilities have closed-loop testing capability, where own EW system effectiveness can be assessed and optimized against threat system sensor systems, and the EP of own EW systems and sensors can be assessed against hostile jamming equipment. An example is the US Air Force EW Evaluation Simulator, which develops and operates validated, high fidelity threat simulators that evaluate US and Allied EW systems' effectiveness in a controlled laboratory environment.

5.4 Measurement facilities

These are used to provide data that cannot be modeled adequately. In some cases, for example antenna pattern measurement (see Electronic Warfare and Defensive Aids Systems Design and Development), they provide data for validation of M&S used in the V&V process. Platform-level measurement facilities used during EW development include EM hazard protection verification on open air test sites and in anechoic chambers (see Electromagnetic Hazard Vulnerability Verification), and RCS and IR signature measurement. Figure 9 shows typical examples.

5.5 Installed system test facilities

Installed System Test Facilities (ISTFs) provide an electromagnetically secure environment for the individual and end-to-end evaluation of EW systems integrated with, or installed on the host platform. They comprise:

- *Aircraft-sized RF anechoic chambers*, in which free-space RF radiation is used to stimulate the SUT and its responses are measured and evaluated. In chamber mode, the SUT can be a whole aircraft with installed DAS or an uninstalled RF EW equipment, Data Link, or other RF transmitter/receiver.

Figure 9. Measurement facility examples. BAE Systems © 2009.

- *Shielded hangars*, for example at Naval Air Station Patuxtent River (USA). Although useful for much EM testing, these are lower performance than aircraft-sized anechoic chambers, restricting EW test capability.

Their main purpose is to evaluate integrated avionic systems in installed configurations to verify specific, platform-level performance against specification. They are also useful for problem investigations and technology experimentation. Chamber cardinal features are indicated in Table 4.

There are relatively few aircraft-sized EW anechoic chambers in the world. An example, the BAE SYSTEMS (Lancashire, UK) EW Test Facility, is shown in Figure 10. Others include the Benefield Anechoic Facility (CA, USA) and Advanced SIL, NAWC Patuxtent River (MD, USA).

These chambers can also be used:

- For IR/UV/Laser, EMC/EMI, Lightning Strike, RCS, and RF Interoperability (including antenna isolation) testing of EW and other RF transmit/receive systems.
- To support evaluation of closed-loop DAS performance against threats in a free-space, EM-secure environment.
- For platform (EW/non-EW) susceptibility testing against High-Power Microwave and other DE threats.

RF threat simulators are essential equipment for EW D&D in SILs and ISTFs. Quantity of RF channels, a significant cost driver, governs their ability to generate complex threat environments. More details on capabilities of aircraft-sized anechoic chamber ISTFs can be found in Pywell and Midgley-Davies (2009) and on RF threat simulators in Pywell (2007).

Figure 10. Example EW anechoic chamber. BAE Systems © 2009.

5.6 Open air ranges

EW DT&E and OT&E are usually conducted on specialist OAR. All known OAR are owned and operated

Table 4. Cardinal features of EW chamber ISTFs.

Feature	Comment
Chamber size	Minimum size around 28 × 18 × 8 m. Largest known chamber: 80 × 76 × 21 m.
Shielding and quiet zones	Usually ≥ 100 dB over at least 0.5–18 GHz. TEMPEST grade. Quiet zones: one or more, dependent on chamber size.
Turntable & crane	Typically in range 30–114 tonnes (turntable) and 30–40 tonnes (crane).
Below ground room	Most have laboratory, data collection or services room below the chamber.
RF/IR threat simulators	• All have RF threat simulators. • Some have communications, navigation, IR scene simulator, radar target generator.
ECM response measurement and analysis	All have some capability, from independent equipment (spectrum, vector network, pulse modulation analyzers) to comprehensive systems like the SMS.
Data acquisition and simulation	All have some capability, for RF, digital and other signal recording and to provide signals to the platform to enable "flight" simulation.
Aircraft and other services	• Cooling, hydraulics, pressurized air, ground power for aircraft. • Fire suppression, control room, CCTV and video recording • Radar Absorbent Material temperature monitoring. • Enclosed aircraft preparation area (some).
Location	Most facilities are adjacent to taxi-way, the flight line or a runway.

by the military, some with civilian contractor support. Most have a combination of multiple real-threat systems, manned/unmanned high fidelity threat simulators ("emulators") and other (lower fidelity) simulators. EW T&E on these ranges is widely agreed to be the next best thing to war-fighting as this is the only "facility" which provides a wholly realistic flight environment. Examples of these ranges include Electronic Combat Range, China Lake (California, USA), Polygone EW Range (Franco/German border), and EW Training Facility, RAF Spadeadam (Northern England).

Although OAR testing can be "war-realistic," there are also a number of limitations and restrictions OAR when compared to testing in chamber ISTFs, SIL, and HITL. OAR flight testing alone is insufficient to provide all required V&V evidence. Major benefits and drawbacks of OAR for EW T&E are given in Pywell and Midgley-Davies (2009).

Even as EW ground test capabilities continue to improve, especially in the area of RF threat simulation fidelity, there will, however, always be a need for flight evaluation of EW systems, especially for development of tactics and training in support of operations and exercises.

6 CONCLUSION

This chapter has described the design and development of airborne EW systems, with emphasis on the self-protection DAS that are essential to survivability. The requirements and specification process have been outlined. It has been shown that robust design and development processes exist that can aid cost-effective development programs for new and upgraded EW/DAS equipments.

The importance of an optimized EW Test and Evaluation process is highlighted, to maximize problem-finding capability whilst minimizing the time and cost of performance verification trials. Modeling and Simulation and aircraft-sized RF anechoic chamber facilities offer great potential for the prevention of problems reaching aircraft and for reduction of expensive flight trials – leaving flight testing to focus on those aspects of EW/DAS that can only be tested in flight.

ACKNOWLEDGMENTS

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NOTES

1. DAS is also known as DASS, Defensive Aids *Subsystem*.
2. Also called Platform Systems Integrator in the UK.
3. DEW is defined in NATO as a subset of EW.
4. UAS, which also means Unmanned *Autonomous* Systems, include UAVs (Unmanned Air Vehicles) and UCAVs (Unmanned Combat Air Vehicles).
5. Dynamic Object-Oriented Requirements System: IBM® Rational® DOORS®.
6. Combat Electromagnetic Environment Simulator, by Northrop Grumman Amherst Systems Inc. ('Amherst').
7. The terms "simulation" and "emulation" are often used interchangeably, with differing views internationally as to their precise meaning. The reader is referred to Pywell (2007) for a discussion of this topic and its importance to EW D&D.

RELATED CHAPTERS

Radar Basics and Applications
Radar Waveforms and Signal Processing
Radar Missile Seekers
Electro-optic Sensor Principles
Electro-optic Imaging and Tracking Systems
The Survivability Balance
Installed Antenna Performance Design and Verification
Electromagnetic Hazard Vulnerability Verification
Electromagnetic Integration of Aircraft Systems

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FURTHER READING

The following references are provided for readers wishing to delve deeper into the EW discipline:

- EW systems design: Schleher (1999) and East (2008).
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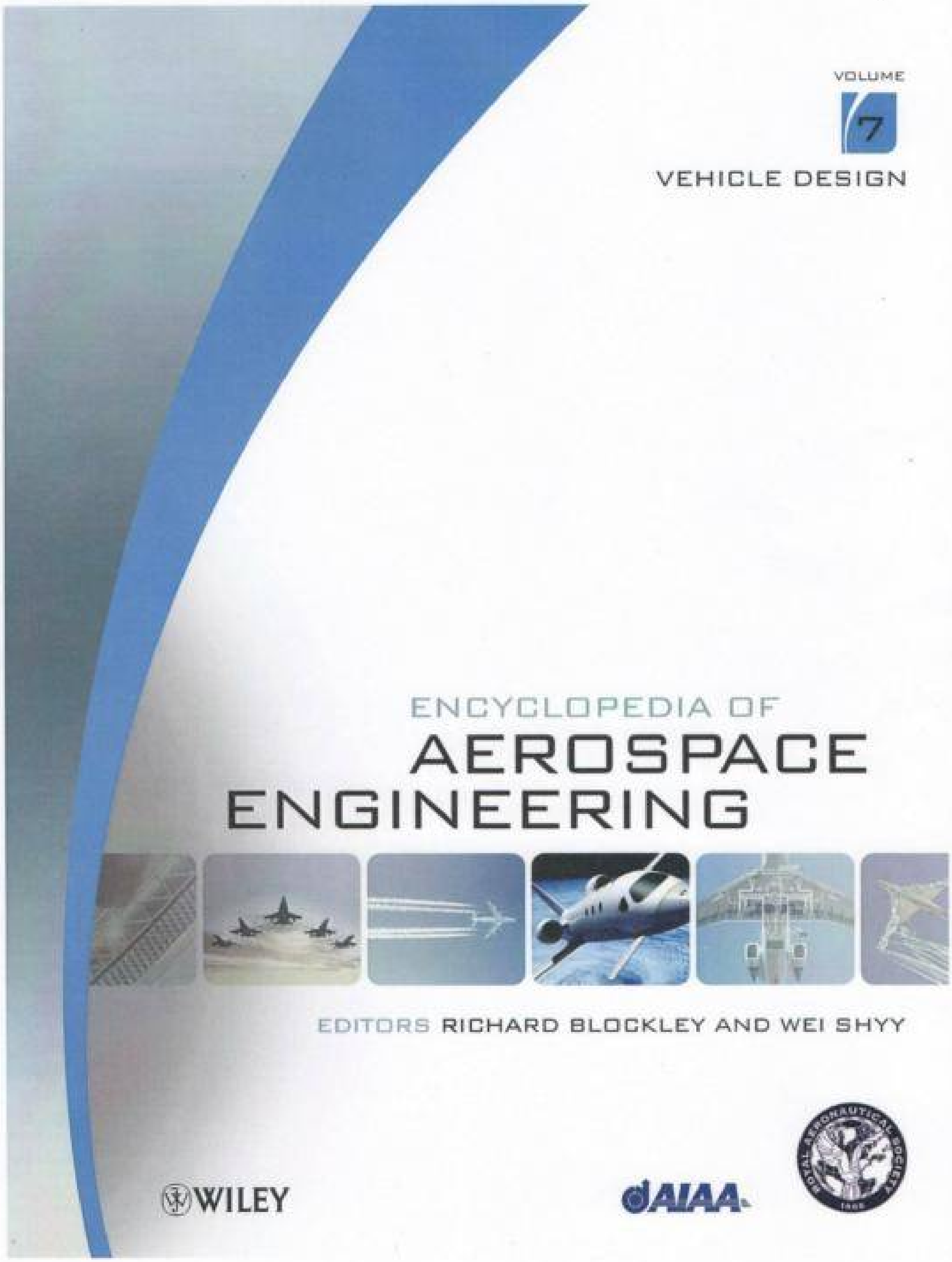

Design Aspects of Aircraft Vulnerability

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1 INTRODUCTION

This chapter provides a description of air platform Vulnerability design. Vulnerability or 'Damage Tolerance' is defined, in the context of this paper, as the susceptibility of airframe and systems to threat weapon effects.

When implemented early enough in the aircraft and weapon system design process, Vulnerability design aspects can contribute significantly to the platform's intrinsic resilience against airframe and systems damage caused by gunfire and missiles. Good Vulnerability design at best allows mission completion after being hit; at worst it enables the aircraft to return to base to be repaired. Inadequate attention to Vulnerability design can lead to unnecessary mission, aircraft, and aircrew loss.

An overview of the Vulnerability topic is provided, design requirements are identified, and threat types outlined. Design aspects are then described: aircraft and systems configuration, structural integrity, and detailed system design and installation. Vulnerability design assessments are explained, divided into qualitative, quantitative, and holistic.

This is an introductory text and focuses on man-made threats, as vulnerability to natural threats is covered in other Survivability chapters, for example, Lightning Strike (Aircraft Design and Qualification for Resilience to Lightning) and Electromagnetic Hazards (Electromagnetic Hazard Vulnerability Verification). Further reading is identified, especially Ball 2003, Pywell *et al*. 1999, and Alonze 1994, which provide topic expansion and sets Vulnerability design in context against other equally important topics of Survivability:

- Vulnerability verification, including Live Fire testing,
- Battle Damage Repair,
- Electronic Warfare (see also Electronic Warfare and Defensive Aids Systems Design and Development).
- Affordable survivability enhancement.

2 OVERVIEW OF VULNERABILITY

As outlined in chapter (The Survivability Balance), Survivability can be subdivided into Damage Avoidance, Damage Tolerance, and Damage Repair. In the case of man-made threats, the former concerns avoiding and evading threat weapon systems and their guidance sensors. Once engaged by a threat system's sensors, then a subset of Damage Avoidance comes into play, that of Evading and Countering the threat

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by various means, usually via the use of Electronic Warfare and its subset, self-protection Defensive Aids Systems (see Electronic Warfare and Defensive Aids Systems Design and Development).

In reality, for most combat situations, the Avoid, Evade, and Counter methods cannot provide an absolute guarantee of survival against the range of threats to be encountered in a given military mission. Such missions include, for example, an aircraft attacking a target or being engaged by an enemy fighter. Under these 'end-game' conditions, where gunfire and/or missile fragments hit the aircraft, Vulnerability of the aircraft against those threats is key to whether mission success can be assured and aircraft and aircrew safe return to base guaranteed.

Low vulnerability yields high survivability – the ability to complete a mission despite damage to the platform. High vulnerability against a given threat means high risk of mission and/or aircraft loss, should that threat successfully engage the aircraft.

As discussed in preceding Survivability chapters (The Survivability Balance and Electronic Warfare and Defensive Aids Systems Design and Development), the most desirable form of improving aircraft survivability is to effectively address damage avoidance, that is, to ensure that the aircraft platform does not sustain any damage that would therefore reduce or deny its operational capability. Such damage avoidance may be achieved by using appropriate operational techniques (e.g., mission planning and tactics), flight profiles (terrain masking), active and passive susceptibility reduction (e.g., IR, radar stealth, optical and acoustic), together with effective counter-measures (e.g., flare, chaff, RF jamming, see Electronic Warfare and Defensive Aids Systems Design and Development). All of these techniques are aimed at ensuring that no threat encounter is successful at causing damage to the airframe.

However, whilst maximizing damage avoidance as much a possible, complete protection of an aircraft platform can never be assured. Even the most effective defensive aids systems can be seen to be ineffective in certain combinations of conditions and threats. Thus one further aspect of aircraft design can provide a final 'line of defense,' that being improved damage tolerance. Commonly known as 'vulnerability reduction' this topic covers aspects of aircraft design which aim to ensure that if hit by a hostile threat, the effects and consequences of damage to the aircraft are minimized.

Vulnerability reduction has many aspects and can be considered at differing levels within the design, that is, aircraft platform, system, subsystem, and equipment. It may also be either active or passive in nature. Ultimately the extent to which vulnerability reduction measures can be incorporated within the design will depend on the requirements of the aircraft program, the wide variety of design constraints, together with operational and life-cycle maintenance considerations and penalties.

3 DESIGN REQUIREMENTS

In modern combat aircraft designs, the manufacturer has to provide optimized overall platform survivability, balanced within the constraints of the program design and consistent with the expected operational use of the platform. In particular, overall platform design constraints including performance and combat effectiveness must be taken into account – this being particularly relevant to aspects of vulnerability reduction, where additional mass penalties, often associated with improving damage tolerance, must be avoided as much as possible.

The need for an integrated approach to Survivability is now generally agreed. In the U.K., the Defence Technology Strategy (Great Britain. Ministry of Defence, 2006a) refers to '*Integrated Mission Survivability*' and defines Survivability as having three components, Susceptibility, Vulnerability, and Recoverability.

Dependent on the national Customer, there may be applicable general design requirements specific to vulnerability reduction. For example, such requirements are contained in Great Britain, Ministry of Defence 2006b and USA. Department of Defense 1997. The design requirements are complemented with defined standards of testing, the results of which are aimed at ensuring a minimum level of damage tolerance within the overall design. Whilst such national standards may be specifically identified as being applicable to a program, typically they can be superseded by the specification of the aircraft.

Typically, the aircraft specification will identify specific aspects of vulnerability reduction required by the Customer – these may be at platform configuration level, or even at detailed equipment level (discussed later in this chapter).

Whilst it is possible to perform vulnerability assessment analyses during the design process, these are generally only suitable in determining relative 'probability of kill' (P_k). By their very nature, absolute values of P_k are difficult to determine, so are not typically found in aircraft specifications. Instead, the Customer expectation is generally that a considered and balanced approach will be taken to ensure appropriate vulnerability reduction measures will be incorporated wherever possible, with the overall aim of improving damage tolerance as far as practicable, and supported by vulnerability analyses as required.

Figure 1. Threat type examples – Air-to-Air Missiles.

4 THREAT TYPES

The type of threat to which an aircraft will be subjected to is, of course, a key issue when considering damage tolerance. In general terms, there are a wide variety of threat types possible.

Firstly, the aircraft's roles, anticipated mission scenarios and mission profiles may be used to identify primary and secondary threats. Such information may be readily determined from the Operational Analysis work contributing to the overall aircraft design process.

Secondly, the detailed nature of threat types must be considered, whether localized damage such as that sustained from Anti-Aircraft Artillery (AAA) and small arms fire are applicable, for example, Figure 8 of Pywell 2004, or the more dispersed warhead fragmentation damage from Surface-to-Air and Air-to-Air Missiles (SAMs and AAMs).

Figure 1 provides an example of two types of AAMs. Section 3 of Pywell 2004 contains unclassified images and further information on these threat types and their capabilities.

AAA tends to result in only a few locations of damage to the aircraft, as typically a small number of separate rounds may be expected to hit the aircraft when damage is sustained in an AAA volley. The rounds are typically 20–85 mm in diameter. Each hit, however, may be expected to result in severe localized damage, due to the use of high explosive or incendiary shells.

SAM and AAM warhead fragmentation damage, however, would be expected to result in a distribution of fragment impacts, potentially very widely dispersed, across the airframe. However, each fragment impact point would be expected to result in quite localized impact damage, mainly to surface structure and equipment items immediately in its direct trajectory. Depending on the likely threats, the selection of the vulnerability reduction measures described in Section 5 may be tailored to provide protection against the damage types expected.

5 DESIGN ASPECTS

There are three key aspects of vulnerability reduction to be considered during the design process, these are aircraft configuration, structural integrity, and detailed system design.

5.1 Configuration aspects

Where possible, this is the control of the general aircraft layout to minimize weapon impact effects. The vulnerability of critical systems can be reduced by optimizing the aircraft configuration, including high-level redundancy, physical layout separation, and change of dimensions.

The configuration aspects of the aircraft design can be the predominant factor governing an aircraft's damage tolerance. Configuration adjustment can be very beneficial to alleviate difficult detailed design problems. The following are important considerations:

5.1.1 Engine location

By the fact of duplicated capability, multiple engines are preferable to single engine configurations – subject to the requirement that multiple engines should be located with physical separation and/or intermediate shielding to ensure that a single hit is not capable of damaging both engines simultaneously. Designs should ensure that unconfined break-up of one engine cannot result in severe damage to, or loss of the other engine.

It should not possible for a fire in one engine bay to spread into the other engine bay or destroy flight critical equipment. A realistic fire protection philosophy needs to be considered to cope with potential fire risks. It is advisable not to locate fuel tanks adjacent to engine bays and in this respect pod-mounted engines are advantageous.

5.1.2 Air intakes and fuel tanks

Engine air intake ducting should be routed to minimize the coincidence of fuel tank and intake walls. If damaged, there is a risk of fuel leakage into the duct, leading to fuel ingestion and risk of engine overspeed and break-up risks. In addition, debris due to the break-up of such structures (worsened by hydraulic ram – see later) may lead to significant ingestion damage.

Unavoidable areas of wetted intake walls should be compensated for by low risk fuel management, which should ensure that critical tanks are drained first.

In addition, where possible, engine intake mouths should be separate to reduce or eliminate the risk of double ingestion of spent gas from a missile burst or shell detonation into both engines simultaneously.

5.1.3 Aircrew

Whilst clear all round visibility may be advantageous to the pilot and other aircrew, the position of the former is highly likely to be significantly exposed and unprotected. Rather, it is advisable to locate the pilot down within the cockpit area, providing natural shielding via surrounding nonessential cockpit equipment. Such natural shielding minimizes the need for consideration of any parasitic protection, for example, protective armor.

5.1.4 Flight control surfaces

There are two alternative concepts for improving the damage tolerance of flight control surfaces.

- Firstly, by minimizing the number of control surfaces. By reducing the area of such surfaces, so the probability of them sustaining damage as a function of overall 'presented area' to the threat is minimized. Although a net mass saving would be expected, the criticality of each remaining surface is increased, with the likelihood that damage to any part will result in the loss of aircraft control.
- Secondly, and contrary to the above, the alternative option is to increase the number of surfaces. By introducing surface 'redundancy' and lowering the criticality of a given control area, any damage may be more tolerable.

Ideally, a combination of both of the above is desirable together with an adaptive flight control system, giving sufficient surfaces to provide redundancy, such that, if damaged, a limited degraded capability remains.

5.2 Structural integrity

It is of primary importance that the structural integrity of the airframe is maintained against the hostile threat. Structural components should not fail following what should otherwise be an acceptable level of damage.

To achieve this, a considered damage tolerant methodology is to be identified and applied across the airframe, which is enabled by an understanding of the expected structural failure mechanisms associated with the identified threat types. Such an understanding comes from experimental investigations, ranging from material level studies up to Live Fire testing against subassemblies and whole aircraft. An example of this Live Fire methodology is provided for the F-22 aircraft in USA. National Research Council 1995 and unclassified images of such testing (shoulder-launched missile fired at F-14 and C-130 aircraft) are contained in Ball and Atkinson 2005.

Only by dedicated testing can a comprehensive understanding be gained of the fundamental damage mechanisms involved and the ways in which the damage propagates.

Currently, structural damage modeling toolsets exist, but these should only be considered as giving indicative results of the levels of damage to be expected – this is especially true for new materials as well as novel combinations of existing types. In essence, vulnerability reduction activities must be underpinned by a knowledge base of structural damage characteristics.

As an introduction, it must be noted that, for aircraft, the nature and extent of structural damage in a given area is significantly affected by the presence of fuel tanks. In essence, if the structure is 'wet,' that is, forming the boundary or internal structure of an integral fuel tank, then the extent of damage sustained can be expected to be significantly greater than that found for 'dry' structure for a given gunfire round or missile fragment. Typical damage characteristics are as follows.

For 'dry' metallic structure, a through hole can typically be expected, depending on the mass and velocity of the projectile, and thickness of structural material. The hole can be expected to have rough petalled edges, which depending on orientation of the projectile, may be relatively circular and similar in size to the projectile, or more jagged and greater in size, see Figure 2. With the exception of the localized effects

Figure 2. Example of metallic structural damage. Reproduced from BAE Systems © 2009.

Figure 3. Carbon composite structural damage example. Reproduced from BAE Systems © 2009.

Figure 4. Assembly fastener pull-through due to hydraulic ram effects. Reproduced from BAE Systems © 2009.

in the immediate area (typically subject to slight denting effects), the remainder of the structure is not unduly affected by the impact.

Similarly, for 'dry' carbon composite structures, the effects of penetration damage tend to be highly localized with delamination in the immediate area surrounding the hole. A degree of surface ply splinters is also commonly observed, see Figure 3.

Conversely to the above, when the structure is 'wet,' significantly greater damage is experienced across the local structural assembly. This is due to the effects of 'hydrodynamic ram,' a phenomenon that acts as a significant damage amplifier. Whilst descriptions of hydrodynamic ram effects can be found in many sources, for example, Ball 2003, effective methods of reducing and mitigating the effects are few.

In essence, the significant projectile kinetic energy is transferred into the bulk of the fluid, causing an initial high pressure pulse and longer term pressure rise (ultimately oscillating within the constraints of the tank), which causes significant internal loading and structural displacement – typically of such a level that the structure does not survive.

'Wet' metallic structures are seen to have similar hole sizes and petalled edges at the impact point, but are often accompanied by massive tearing effects with deformation and displacement of skin panels. Composite damage can be equally destructive, but is typically less visually impressive. Rather than the tearing and peeling-back of the skin, composites will typically outwardly show only a relatively minor hole, as per dry damage. Not visible to the eye will be the massive and extensive multi-ply delamination through the thickness of composite skin around, and extending some distance away from, the impact point. This is caused by the large displacements of skin due to the internal loading pressures resulting from the displaced fluid. Typically, this will be accompanied by the 'pull-through' of fasteners in the surrounding area and extensive substructure damage, see Figure 4.

5.3 Detailed system design and installation

This is the control of system or subsystem vulnerability by applying various techniques at system, subsystem, or component level. Once the aircraft's configuration has been defined, improved damage tolerance may be incorporated within the design by consideration of the principles in the following subsections.

5.3.1 *Duplication*

The normal design practices of duplication provide a sound basis for the duplication necessary to improve damage tolerance, for example, duplicated hydraulics and fuel tank groupings. However, these standard precautions only partly satisfy the requirements of damage tolerance. The function of such systems must be designed so that faulty operation of one duplicate, due to damage sustained, does not affect the correct operation of the other. System design must ensure that effective duplication exists for the instances of battle damage – particularly with respect to potential multiple hits. Aspects of cross-comparative control systems must consider such aspects in particular.

The concept of duplication can be extended to component level, where any duplex functionality can be separated by adopting a good internal arrangement, and by the use of suitable construction techniques for the equipment.

In general, the degree of duplication must be consistent across all essential systems and it is inadvisable to include the use of singly critical equipment. However, where such critical equipment are unavoidable and where these are essential for flight, they should not be distributed throughout the airframe as the chance of damaging any given one is increased, possibly resulting in aircraft kill. Hence, for this reason and for this type of component, the overall risk is reduced by grouping them together. The chance of hitting any one of them is thus confined only to those cases of damage to their specific location.

Since battle damage, of a degree that is potentially survivable, tends to affect only a certain proportion of the aircraft area, the benefits of duplication rely heavily on the relative physical locations of the system functionality – such that adequate physical separation must be achieved.

5.3.2 Separation

In general terms, the design aim must be to achieve adequate physical separation. However, the definition of 'adequate separation' must be carefully considered with respect to the applicable threat types. Whilst maximum separation, for example, separate sides of the aircraft, may be desirable, other penalties of such a design may be severe (e.g., installation complexity and maintenance penalties).

It is therefore critical to adequately determine and define the aircraft primary threat, and the corresponding damage characteristics expected. Where extensive local damage may be expected, for example, significant separation requirements may be considered excessive and unnecessary. Conversely, where dispersed fragmentation damage may be expected, maximum separation requirements may be appropriate. Geometric arrangements also need to consider probable threat approach directions to ensure effective separation.

It is important to note that effective physical separation of duplicate systems is not just defined in terms of separation distance, but also the extent of shielding provided by nonessential equipment. Both are required to minimize the risk of coincident damage occurring (i.e., one hit damages both).

Design integration activities must note and consider which functions are considered essential (either duplicated or singly), and also ensure adequate separation from potential sources of secondary damage effects. The presence of high temperature or pressure pipe work, fuel lines, and the like may result in secondary effects such as fire or explosion damage, potentially resulting in the loss of critical functionality. Figure 5 illustrates possible pipe-work damage. Duplicated hydraulic lines, if routed through the same fuel tank area, could suffer coincident damage as a result of a single hit causing hydraulic-ram damage to the tank.

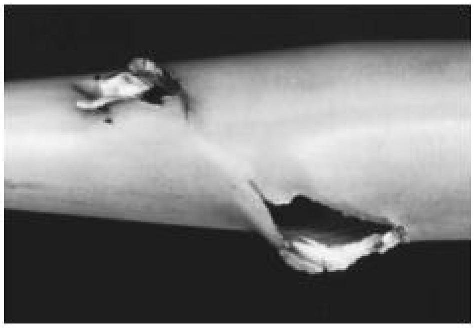

Figure 5. Pipe-work damage example. Reproduced from BAE Systems © 2009.

5.3.3 Shielding

There are two main types of shielding, the first is known as 'natural shielding' and involves the conscious grouping and layering of components within the installation design of the airframe. The second is a type of 'parasitic protection', discussed in Section 5.3.4.

Natural shielding relies partly on sacrificing mission system components in order to protect flight critical components. This can be complemented by locating critical components behind heavy structural items wherever possible.

It is useful, when organizing the installation layout, to list components involved and rank them in order of flight criticality or mission capability. The most important components can then be located in the most sheltered positions, relying on the protection from surrounding components. One of the most useful shielding media can be fuel and, if specific tanks can be considered as 'expendable' in terms of their content, these could be used to provide natural shielding for essential components – subject also to adequate tank fire and explosion reduction techniques.

The concept of adequate shielding can also be extended to component level. Internal arrangement and construction of equipment can, in principle, enable incorporation of separate duplex internal functionality.

5.3.4 Protection

Vulnerable components sometimes need to be protected by adding armor plate between them taking into account probable threat approach directions, but this should only be used in critical areas where natural shielding is considered inadequate.

The addition of armor protection is a crude and wasteful method of 'parasitic protection' and should be considered only as a 'last resort.' The term 'parasitic protection' relates to the expected mass penalties associated with such a technique, however, dependent on the locations considered, the mass additions may be offset against aircraft ballast requirements necessary to ensure correct aircraft center of gravity range. In general, the incorporation of such protection indicates that the aircraft design has a poor inherent damage tolerance capability, typically due to inadequate consideration of vulnerability aspects early enough in the project design process. Early attention to the main vulnerability features can ensure that adequate natural shielding is designed in, making parasitic protection unnecessary.

Other types of protection may be necessary, depending on the type of systems and the configuration adopted. Some examples are fire suppression, fuel tank self-sealing, explosion suppression, and hydrodynamic-ram protection.

5.3.5 Isolation

Isolation is concerned with the containment of damage effects at a system level. In essence, it is the identification of key functional aspects of a system and drawing a distinction between those which are considered to be 'essential' and those deemed 'desirable' – in the context of post-damage aircraft survival. Essential core functionality needs to be preserved when damage occurs to the system in areas classed as only 'desirable.'

A good example of this is a protected hydraulic system whose essential capability is to maintain a minimum level of flight control actuation, with an isolation function able to separate other desirable hydraulic circuits if damaged. Another example is the addition of cross-feed and tank interconnect to a basic fuel feed system. These are desirable functions, but must not compromise the main feed functionality by adding extra risks.

5.3.6 Component damage tolerance

Individual hits by rounds or warhead fragments can in themselves cause secondary damage mechanisms when they hit aircraft components. It would be required that certain types of potentially 'high risk' components have an inherent design which minimizes any form of damage amplification.

For example, a high-pressure fluid reservoir should be designed and tested to show a restrained break-up characteristic when hit, rather than breaking up into a multitude of high-speed fragments, each capable of causing further extensive internal damage.

6 VULNERABILITY DESIGN ASSESSMENTS

6.1 Assessments as part of the design process

As previously noted, aircraft specifications are not normally specific in quantifying absolute 'probability of kill' (P_k) requirements for an aircraft design. Rather, it is expected that a balanced approach is taken, combining damage tolerance considerations within the overall design process to reach a suitable design solution which addresses key factors, as appropriate to the program. To this end, vulnerability assessments must be considered as an integral part of the overall design process.

The primary aims of the assessments are to:

- identify and evaluate the inherent vulnerability aspects of the proposed design,
- incorporate and assess detailed design changes aimed at improving specific damage tolerance issues,
- assess improvements at an aircraft level, to determine their overall effectiveness,
- determine associated penalties for subsequent design trade-off studies.

The assessment methodology adopted and the degree of design consideration will reflect the level of emphasis placed on damage tolerance by the specification and program in general. In principle, the approach taken may be one of a qualitative or quantitative assessment. Typically, relative assessments are undertaken, comparing two or more design definitions to determine the value of damage tolerance characteristics within the design. The analysis considers in detail the final stage of a hostile encounter, such that the threat system has engaged with the aircraft.

In the case of gunfire, a range of intercept trajectories through the aircraft would be considered. For missile engagements, weighted approach direction, fuzing distance, and warhead fragmentation characteristics would be considered to determine the likely fragmentation impact points across the airframe.

When undertaking the assessment, a range of aircraft kill types may be considered, determined primarily by the engagement timeframe of the analysis. The analysis may consider only an 'immediate kill,' say within 3 s, such that the occupant is unlikely to have sufficient time to safely eject – thereby assessing the survivability of the crew.

Alternatively, the assessment may consider a typical timeframe to enable a successful return to a friendly airfield, known as a 'Return to Base.' Such analyses take into account additional aspects of the design, such as maintaining engine fuel supply, provision of navigation information, and landing functionality.

6.2 Qualitative vulnerability analyses

Survivability engineers should carry out an independent assessment of the aircraft design, taking into account type of aircraft, specification requirements, mission threats, and detailed design solution. More specifically, when undertaking an assessment, the engineer should initially:

- Determine platform definition and configuration(s), the primary and secondary threat mechanisms expected, and acceptable levels of degradation.
- Construct a comprehensive dataset of aircraft design information. Ideally this should include the installation of main flight critical systems and primary structure, functional schematics for critical systems, summary of structural materials and their locations, and definition of any incorporated protection measures.
- Determine threat characteristics, in terms of points-of-strike within the mission profile, expected engagement geometries, likely aircraft maneuver and fuel states at time of strike.
- Collect relevant vulnerability test data relating to the behavior of structural materials and critical components.

Based on the above, a qualitative assessment can be undertaken to identify those critical components most likely to sustain damage, wherever possible assessing the likely extent of damage based on estimated intensity of damage.

- Firstly, structural items should be considered, comparing results gained to a range of pre-existing damage tolerance assessments to assess the relative risk of aircraft loss.
- Subsequently, these items should be evaluated:
  - Duplication and separation of essential systems should be considered to determine if duplicated critical functionality are likely to receive coincident damage, leading to aircraft loss.
  - The approximate depth of structure and systems around the critical systems and the evaluation of the degree of shielding provided.
  - The general layout of dry bays close to fuel tanks should be examined, to assess the risks of fuel leakage and subsequent fire or explosion.
- The above should be followed by the identification and assessment of potential secondary damage amplifiers, as discussed previously.

Observations should be presented in an order that reflects the seriousness of damage and the approximate probability of damage occurring. Results should summarize the observations made in terms of the relative risk of the aircraft being killed within the timeframe considered.

6.3 Quantitative vulnerability analyses

As with the qualitative assessment, the Survivability engineer needs to compile the range of design data, but typically to a greater level of detail. This is necessary as the quantitative assessment usually employs an automated toolset to process the analysis, considering the detailed layout of equipment geometries (see example in Figure 6), threat engagement conditions, and system functionality within a detailed numerical model.

A number of toolsets have been developed by a wide range of institutions over many years, for example those at the U.S. Survivability/Vulnerability Information Analysis Center (SURVIAC) (USA. Department of Defense, 2010), some relevant examples of which are listed here:

- COVART – Computation of Vulnerable Area Tool
- FASTGEN – Fast Shotline Generator
- FATEPEN – Fast Air Target Encounter Penetration Program

Typically, such toolsets are restricted in nature due to the confidential nature of the embedded damage-tolerance datasets. However, a number of commercially available applications exist, for example, FASTGEN IVAVIEW® (visu-

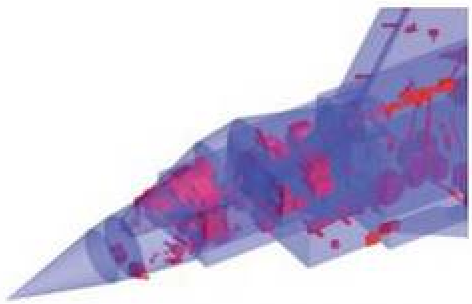

Figure 6. Quantitative vulnerability modeling – example selection of components. Reproduced from BAE Systems © 2009.

alization tool for use with FASTGEN), and may be sourced to perform such quantitative assessments.

Such toolsets can provide a robust statistical assessment of damage cases, over a wide range of encounter conditions, thereby improving the level of confidence in the results obtained.

6.4 Holistic vulnerability analyses

Irrespective of the type of assessment performed, be it qualitative or quantitative, their primary value is to assess the effectiveness of vulnerability reduction aspects of the design at an aircraft level.

Due to the nature of threat types and inherent aircraft design issues, the incorporation of specific damage tolerance techniques will no doubt provide individual benefits by addressing specific vulnerability issues. However, it is often found that when one kill mechanism is addressed, another simply replaces it as the primary cause of aircraft loss.

Thus by performing a full aircraft analysis the individual vulnerability issues are not considered in isolation, but instead are all considered in parallel, providing a holistic view of susceptibility to threat weapon effects. The results gained can provide clear guidance on the overall benefits, or otherwise, to be gained from the incorporated vulnerability reduction techniques. Often it is found that damage tolerance has to be applied in a consistent and holistic approach across the airframe to gain any positive advantage at an aircraft level.

6.5 The importance of iterative analysis

As the design progresses and difficult compromises are required to achieve other requirements, it becomes more appropriate to adopt a quantitative approach to vulnerability analysis. It is also important to revisit a holistic whole aircraft analysis from time to time through the design process to ensure that one protection mechanism has not worsened vulnerability in another area.

During the service life of a platform it is also important to revisit, as appropriate, relevant parts of the preceding analyses to ensure that the impact on Vulnerability is not unacceptably degraded by proposed modifications to the airframe and systems contained therein.

7 CONCLUSION

This chapter has provided an introduction to the specialist topic of Vulnerability design. It has described the many complex and interrelated design aspects and considerations necessary to enable aircraft with appropriate and affordable levels of resilience to man-made threats – Surface-to-Air and Air-to-Air Missiles, Anti-Aircraft Artillery shells, and small arms fire.

Key points made are:

- Vulnerability design and assessments must be conducted early in the aircraft overall design process if that aircraft's Damage Tolerance is to be maximized and optimized.
- To be of most use, Vulnerability modeling and assessments must make use of empirically derived data on actual damage mechanisms.
- Gathering such underpinning data, especially as much is platform type-specific, is a significant and ongoing task and most of the data is confidential.
- Toolsets have been developed to conduct and aid Vulnerability design and assessments. Although many are restricted access, there are now a number of commercially available packages. Such packages, however, still need the type-specific underpinning data to assure robust Vulnerability solutions and recommendations.
- Only by paying adequate attention to Vulnerability design at project outset can mission success probability and aircraft/aircrew survival be maximized. Failure to do so can lead to unnecessary and expensive mission failure and loss of aircraft and aircrew.

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RELATED CHAPTERS

Models for Delamination
Techniques for Damage Tolerance and Structural Integrity of Composite Structures
Electronic Warfare and Defensive Aids Systems Design and Development
Electromagnetic Hazard Vulnerability Verification
The Survivability Balance
Aircraft Design and Qualification for Resilience to Lightning

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FURTHER READING

The following provide further information for the interested reader on the topics covered in this chapter:

- Survivability: Ball 2003, especially Chapters 5, 'Vulnerability' and 1.6 'Testing for Survivability'.
- U.S. SURVIAC web site: www.badayton.com/index.htm
- Tactical Missile Warheads: Carleone (Ed., 1993).
- Live Fire Testing of the F-22 Aircraft: ISBN 0-309-05333-1

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Developments in RF simulator technology – approaching the affordable fidelity limit

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ABSTRACT

Technology developments in radar frequency simulators of the type used to verify the performance of complex electronic warfare systems are described. The successful verification of this performance prior to combat use is a necessary pre-requisite of military platform survivability and mission success. These simulators and associated modelling and analysis tools have enabled a major shift during the last 15 years from expensive and limited flight trials to repeatable laboratory and anechoic chamber tests, although they will never totally supplant those trials. Most limitations of the early days of many-channel simulators, 25 years ago, have been resolved or adequately and – as importantly – affordably mitigated, largely enabled by computing power increases. Limitations remain that will, within affordability constraints driven by Defence Ministries world-wide, prevent perfect simulation ('emulation') and the attendant, tantalising but utopian goal of laboratory and chamber test results that *precisely* match those from flight test and combat.

NOMENCLATURE

AMES	Advanced Multiple Emitter Simulator
AMOP	amplitude modulation on pulse
BAF	Benefield Anechoic Facility
AOA	angle of arrival
CEESIM	Combat Electromagnetic Environment Simulator
CHAFF	chopped aluminium Foil
CP	circularly polarised
CW	continuous wave
DF	direction finding
DTO	digitally-tuned oscillator
ECM	[RF] electronic countermeasures (jammers)
ELINT	electronic intelligence
EOB	electronic order of battle
ESM	electronic support measures
EW	electronic warfare
EWsT	EW Simulation Technology Ltd.
FLO	frequency-locked oscillator
FMOP	frequency modulation on pulse ('chirp')
HFIM	high-fidelity intra-pulse modulation
HSS	high-speed synthesiser
ID	identification
LCC	life cycle cost
LPI/LPD	low probability of intercept, detection
MPPS	mega-pulses per second
OAR	open air range
PD	pulse doppler
PMOP	phase modulation on pulse
PRI	pulse repetition interval
PW	pulse width
RF	radio/radar frequency

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RSS	Radar Signal Simulator
RWR	radar warning receiver
Rx	receive(*r*)
SEI	specific emitter identification
SNR	signal-to-noise ratio
STS	slow-tune synthesiser
SUT	system under test
T&E	test and evaluation
TDOA	time difference of arrival
VCO	voltage-controlled oscillator
UMOP	unintentional modulation on pulse
VV&A	verification, validation and accreditation

1.0 INTRODUCTION

This paper considers technology developments in radio/radar frequency (RF) threat simulators, hereafter referred to as 'simulators', as used for the test and evaluation (T&E) of electronic warfare (EW) receiver and processing systems. It focuses on commercially available large simulators operating in the modern-day most important radar band (0·5-40GHz), as used in EW laboratories and anechoic chamber facilities world-wide. It draws on BAE Systems' considerable experience in this area with two of the world's major simulator types – CEESIM and AMES†. These simulators comprise the computing, digital and RF components necessary to generate RF signals for injection into, or radiation at, EW receiver systems. Figure 1 shows the range of such simulators.

T&E in this context comprises activities conducted in support of the design, development and in-service support of EW receiver systems on air, sea and land platforms. Such systems, see Fig. 2, comprise radar warning receivers (RWRs), electronic support measures (ESM), electronic intelligence (ELINT) systems and electronic countermeasure (ECM) receivers – generically known as systems under test (SUTs). RWR/ESM are fitted to most military aircraft that have to go in harm's way, with ECM also fitted to higher value assets and those who cannot avoid engagement by deadly threats. RWR/ESM/ELINT cardinal capabilities of direction finding (DF), emitter/platform identification (ID) and emitter location are covered elsewhere, e.g. Ref.1.

† Advanced Multiple Emitter Simulation (AMES) simulators, originally produced by Advanced Systems Development Inc. (New York, USA), are now produced by Northrop Grumman, Amherst Systems Inc., Buffalo, USA. Combat Electromagnetic Environment Simulation (CEESIM) simulators have always been produced by the same Amherst Systems Inc.

Figure 1. Typical CEESIM threat simulators.
(© Northrop Grumman, Amherst systems Inc.)

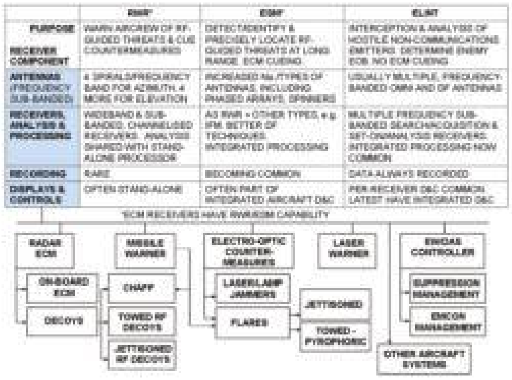

Figure 2. Receiver systems in airborne EW suite.

These simulators, which usually involve multi-$M capital expenditure, are essential for SUT development and support. In turn, these SUTs are crucial to assuring platform survivability and thus mission success. As the international community strives to achieve optimum survivability through platform-specific balancing of stealth (radar, infra-red and other signatures), EW systems, electromagnetic hardness and intrinsic aircraft vulnerability,[2,3,4,5] the importance of simulators has grown.

Key requirements for RF simulators and their use in the EW T&E process are stated. Simulator suppliers and top-level capabilities over the last two decades are outlined. Technology and performance enhancements are then described in terms of importance to RF environment simulation fidelity. The thorny question *'Is perfect simulation ('emulation') of the operational air RF environment realistically achievable using RF simulators and is it really warranted?'* is then addressed, with reference to *why* higher fidelity is actually needed.

EW receivers and consequently simulators operate in the same technical parameter space, since all operate generally with the same RF threat environment. No requirement or numeric herein is thus intended to be associated with any specific SUT, platform or programme. Likewise, this paper does not discuss emitter databases. These are essential to SUT and simulator operation, but are nationally sensitive. Ref.6 gives an unclassified insight into database use in the EW T&E process.

2.0 KEY SIMULATOR REQUIREMENTS

This section identifies simulator requirements, purpose and benefits. It outlines test mission types and locations, discusses platforms and the EW measurement techniques used to identify and locate threat emitters, and describes the resultant attributes of simulators required to prove those systems work correctly.

2.1 Laboratory *vs* flight correlation and overall T&E affordability

For decades there has been world-wide bad press concerning EW systems and their alleged poor combat performance. In particular this criticism has been aimed at EW receiver systems and their ability to correctly identify and locate life- and mission-threatening enemy weapon systems. The origins of this oft-justified criticism, that triggered much of the effort that resulted in the comprehensive simulators now available, can be traced to the Vietnam War where the loss of aircraft to Soviet SA-2 missiles focused the minds of the EW community on higher quality threat detection and better tactics and countermeasures.

The main problem faced by the scientists and engineers of the time was the great difficulty in reproducing combat and flight test results on EW receiver systems in the laboratory for all but the simplest test cases. Even today this complex problem is not wholly resolved and this is discussed later. Of equal emphasis was and remains overall EW and T&E process affordability[3]. To fully develop a new or upgraded EW receiver system wholly by the then traditional fly-fix-fly method became unaffordable, in time and money, over a decade ago. The T&E community subsequently developed capabilities that allowed tests to be transferred, wherever possible, from flight test to aircraft ground test, to avionics/systems integration laboratories, to sub-system and equipment test laboratories, to *validated* modelling. As simulator, laboratory and anechoic chamber capabilities have grown, the need for expensive EW flight testing has reduced.

2.2 Simulators in the EW T&E process

Simulators provide controlled and repeatable RF emitter environments, primarily for developing SUTs and proving their compliance to specification via laboratory and aircraft ground/flight trials. Threat DF and ID are the two cardinal parameters to be proven, where DF has moved from azimuth-only 20 years ago, through azimuth and elevation 5-10 years ago, to the most recent developments towards precise and fast geo-location from long ranges.

It is useful to understand what is meant by 'emitter' and 'threat emitter' in the context of simulators. An emitter is a military or civilian RF-generating system on land or on an air, sea or land platform. It is usually a radar- or radio-based system, e.g. air traffic control radar, ship's search radar. A 'threat emitter' is one or more of the radars associated with a weapon system that might pose a hazard to one's own platform. A good example is a surface-to-air missile system's search, target tracking and fire control radars, see Fig. 3. Ref.4 gives a description of such threats and Table 2.3 of Ref.7 provides an indication of their RF parameters. The ability of an EW system to quickly and accurately determine the ID and location of threat RF emissions incident on the SUT's antennas is crucial to mission success and platform and crew survival. This survival is usually enabled through engagement of optimal tactics and threat countermeasures, e.g. RF jamming, flares, CHAFF and directed infra-red countermeasures.

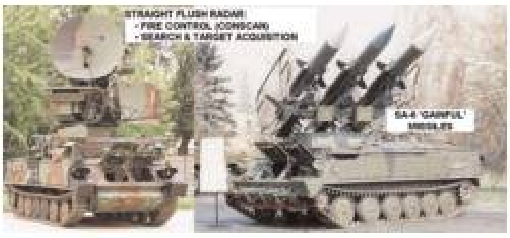

Figure 3. SA-6 surface-to-air missile system. (© Reproduced with permission of Jane's Information Systems).

Terms used to describe the above 'proving' process, generically known as the 'EW T&E process', include validation, qualification, verification and certification. The precise definitions of these terms, which can vary between and within countries, and the interaction and overlap between activities conducted under each term are outside the scope of this paper. Whilst EW T&E processes vary between countries, many aspects are similar. Readers wanting a better understanding are referred to *'Electronic Warfare Test and Evaluation'*.[5]

The prime simulator factors applicable to this process are:

1. Does the RF signal at the simulator output accurately represent the RF environment as would be encountered by the SUT in real life?
2. Does the SUT meet its specification when tested with the simulator?

Regarding item 1, it is important to realise that simulators need to generate 'truth' (sometimes known as 'ground truth') data in terms of RF environment, i.e. irrespective of the SUT's capability to measure that environment. The fidelity level necessary to support this is discussed in Section 5.0. This truth data is then compared to measured data from tests/trials. Error budget analysis and application of pass/fail criteria completes the proving process.

Simulators are also used for in-service support of platforms, including mission data validation pre-combat, aircrew/groundcrew training and problem evaluation. Their use during design, development and in-service support is elaborated in Section 2.4.

To support the above, simulators contain various modelling elements with their computing component. That component's outputs are used to digitally control the simulator's RF output components. Figure 4 gives a schematic of a generic simulator, with the main features of the above modelling elements.

Simulators also have to produce operationally realistic quantities of RF emitters, with consequently high pulse densities, in real-time and with high accuracy and repeatability. Together, these needs combine to create an extremely demanding computing, digital and RF technology requirement that remains challenging.

2.3 Benefits of simulators

The primary benefits of simulators are:

1. **Reduces cost and provides more repeatable testing than by flight trials.** Maximises cost-effective execution of SUT performance verification tests to support contract compliance. Optimises overall test repeatability and efficiency when test stimulus commonality is achieved between EW equipment supplier, platform/system integrator and military user.
2. **Finds problems earlier in programme,** in the laboratory and chamber, yielding faster and less costly fixes than for those

KEY COMPONENT	CARDINAL FUNCTION	MAIN FEATURES
RF EMITTER MODEL	PULSED & CW RF WAVEFORM GENERATION	SIGNAL PARAMETER DEFINITIONS e.g. · FREQUENCY, PW, PRI, POWER · MODULATION PARAMETERS
	TRANSMIT ANTENNA CHARACTERISTICS	EQUIPMENT CHARACTERISTICS e.g. · BEAM AND SCAN PATTERNS, RATES
PROPAGATION & ATMOSPHERIC EFFECTS MODEL	SIGNAL TRANSMISSION EFFECTS BETWEEN SUT ANTENNAS & EACH EMITTER	· ABSORPTION ATTENUATION, DUCTING · SURFACE TYPES (SEA STATE & TERRAIN ROUGHNESS) · MULTIPATH (SEA, LAND, OTHER PLATFORMS) · POLARISATION EFFECTS · TERRAIN SCREENING/BLOCKING · EMITTER-SUT RELATIVE GEOMETRY · DYNAMICS OF OWN PLATFORM & EMITTERS
SUT ANTENNA & RECEIVER MODEL	SUT & HOST AIRCRAFT EFFECTS	· ANTENNA PATTERNS & DISPOSITIONS ON AIRFRAME · DF TECHNIQUES, e.g. PHASE COMPARISON, TDOA · RECEIVER THRESHOLD MODELS

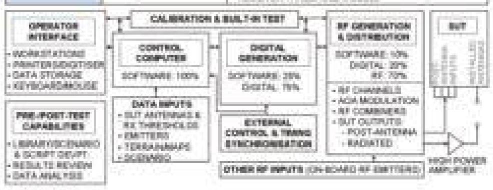

Figure 4. Simulator schematic and key modelling elements.

problems discovered later in the programme. Increases SUT maturity at the earliest time in the programme and minimises over-run risk. Discovering >90% of problems via laboratory and chamber testing is nowadays a common goal.

3. **Reduces risk of technical under-performance** on SUT delivery to military user.
4. **Reduces schedule risk** – design and development through to Operational Readiness Statement.
5. **Enhances operational support:** assists operational evaluation prior to service release. Enables high fidelity RWR/ESM/ECM mission data validation, tactics and RF countermeasures optimisation, and realistic training and mission rehearsal prior to combat use. Increases confidence in EW system performance under combat conditions. Enhances ability to repeat, isolate and resolve operational problems via highly controlled test conditions.

Useful examples of simulator usage and benefits are covered in a number of publications[8,9,10].

2.4 Test mission types and content

Simulator requirements can be derived from a consideration of the SUT's specified performance, SUT-specific threats, other RF emitters and test missions. Table 1 shows an approximately chronological series of test missions *vs.* locations for newly developed or upgraded EW systems. It is relevant to note that aspects of each are relevant to industry, whose interest is predominantly in successfully complying with the SUT's specification verification matrix (and thus getting paid), and to the armed forces, whose primary focus is mission success, maximum survival probability and minimum operating and life cycle costs.

Simulators are configured for SUT testing in two ways, directly coupled and radiated. In the first case the SUT antennas are removed and the RF signal is injected into the SUT's antennas' cables, with the simulator containing a receive aperture/antenna model for each SUT antenna. This method is also known as 'post-antenna injection'. In the radiated case the RF signals from the simulator are not processed by the aperture/antenna model, but are routed to high power amplifiers and thence to transmit antennas within the anechoic chamber or on the flight test/trials range (aka open air range [OAR]). Figure 5 shows an aircraft undergoing such testing in BAE SYSTEMS' EW Test Facility, with a transmit antenna stack inset.

Table 2 shows the primary areas of interest when testing EW receiver systems with simulators.

Table 1
EW test mission vs test location

Test Location	Primary Test Mission
Laboratory (RF, Intermediate Frequency and digital-level)	R&D and concepts evaluation. Note: Often need threat simulation capability enhancement to be able to develop new or 'next generation' EW receiver systems/upgrades
	Requirements definition & system performance modelling
	Hardware In The Loop: Equipment/sub-system development/qualification
	Uninstalled sub-system performance verification (usually over full ranges of performance) Integration with other platform avionic systems; further development & un-installed performance verification, conducted in Systems/Avionics Integration Laboratory
	ESM-ECM performance optimisation vs. specified threat environment
	Evaluation of new/upgraded threats & countermeasures development.
	Development, evaluation & clearance of EW upgrades
Anechoic Chamber	Platform-system integration. Further sub-system & integrated avionics system development
	Installed system performance verification, including SUT irradiation with 'war-mode' & other signals not allowed to be transmitted in the open air Fault/anomaly investigation, isolation & solution confirmation
Open Air Test Site	Airframe-systems aspects of EW upgrades' development, evaluation & clearance Free field irradiation of aircraft-installed SUTs for cases where anechoic chamber tests not viable or unacceptably limited, e.g. antenna polar diagrams & ESM-ECM beam-forming measurements. Whole platform electromagnetic compatibility tests Component & platform radar cross section measurement
Flight Test Range	Residual installed performance verification tests for aspects not acceptably testable using above locations/methods Development & performance verification of aspects not ground-testable, e.g. combinations of tactics, flare/chaff dispensing, on-board RF jamming & towed RF decoys Evaluation/optimisation of EW system man-machine interface under flight conditions
In-Service Support (Laboratories and 'Open Air' Training Ranges)	Mission Data Validation prior to and during training, operational evaluation & combat
	EW hardware/firmware & algorithmic software performance optimisation Post-maintenance/pre-flight check-out Evaluation/resolution of operational problems
	EW & countermeasures/tactics effectiveness evaluation/optimisation
	Mission rehearsal & aircrew/operator/maintainer training

Table 2
EW receiver system tests

Probability of Intercept/Detection	Emitter Identification (correctness; lack of ambiguity)
Time to correctly ID emitters (threat and non-threat)	Threat DF/AOA accuracy
Threat range/pseudo-range (accuracy)	Threat location (Circular/Elliptical Error Probability)
Threat prioritisation (correctness of)	False Alarms (quantity and rate)
Missed alarms and non-detection/display of threats	Defensive/Offensive sub-systems' cueing/triggering

2.5 Platforms, SUTs and measurement techniques

Simulators are used to test EW receiver systems on a wide range of platforms, e.g. unmanned air vehicles, fighters, helicopters, bombers and larger aircraft. In the case of laboratory-based tests, a large part of a simulator is common across platform types. The area that invariably differs is the SUT interface. Primary differences are:

1. Frequency band(s).
2. Antenna types, gains, polarisations, numbers and disposition on the platform.
3. Signal handling capability, aka 'pulse density', for continuous wave (CW) and pulsed signals.
4. Receiver CW/pulsed emitter detection (sensitivity) thresholds.

Figure 5. Radiated EW tests in anechoic chamber.
(© BAE SYSTEMS).

Table 3
Emitter DF and location techniques

SUT Technique	Typical r.m.s. DF accuracy	Application on platforms
Amplitude Comparison	3-15°	4-port is minimum capability of EW receiver systems
Phase Interferometer	0.1-3°	Often forward azimuth coverage only on aircraft
Spinner	2-5°	Not normally applicable to fast jets
Multi-beam, Electronically Scanned Arrays	1.7-2°	Originally land and naval/army platforms; finding increasing use in aircraft
Time Difference of Arrival (TDOA)	<2°	Complex, especially on aircraft, and needs large platform for highest accuracy

5. Measurement techniques utilised by the SUT's receiver and processing elements.

With the exception of item 5, these are discussed later in this paper. Whilst detailed discussion of various direction finding and emitter location techniques is adequately covered elsewhere, e.g. Ref.7, the main techniques are summarised in Table 3. It is of note that, with the advent of 'digital receivers',[11] SUTs are being developed that use combinational techniques, e.g. time difference of arrival (TDOA) with frequency difference of arrival ('differential doppler'), thus optimising overall performance by mitigating individual techniques' ambiguities and other limitations. In pursuit of the militarily high priority precise geo-location of threats, multi-platform solutions are under investigation in a number of countries. Despite the need for high bandwidth data-links, they offer superior accuracy to single platform solutions.

Types of SUT antennas include spiral (single and dual-polarisation), log-periodic and horn (static or with/without spinner). Figure 6 shows an example of the most commonly used EW antenna, the cavity-backed spiral, in this photograph a dual circularly polarised version.

2.6 Resultant RF simulator attributes

Consideration of the requirements of Sections 2.1 to 2.5 yields a cardinal point simulator specification that can be tailored to the SUT to be evaluated. Table 4 gives a view of typical specification elements for a generic simulator, as gleaned from open-source marketing material, e.g. supplier web pages[12,13] and market surveys done by this author. Whilst the table clearly indicates the complexity of a modern simulator, it is not intended to be definitive or exhaustive. A typical cardinal point specification is 10-20 pp. whereas a 'best-practice', detailed contract specification for a large simulator is 140-170 pp. As this suggests, much detail is required to precisely define what is meant by the terms in Table 4.

3.0 RF THREAT SIMULATORS – THE PAST TWO DECADES

This section outlines the origins of simulators and differentiates between the size of simulators in terms of the primary differentiator (other than SUT interface and RF source type) – number of RF channels. For large, 'many-channel' simulators, the subject of this paper, the limited number of companies and models commercially available during the last 20 years is explored.

Figure 6. Typical EW receive antenna.
(With permission, TECOM Industries, Inc).

3.1 Origins of RF simulators

Prior to the advent of modern day commercially available simulators in the late 1970's, threat emitter simulation was realised at the simplest level by the use of a CW signal generator, a voltage-controlled oscillator (VCO), feeding either the SUT (post-antenna) or an amplifier and antenna for free space irradiation of the SUT's antennas. Addition of a microwave PIN† diode modulator, driven by a pulse signal generator, allowed simulation of simple pulsed signals – usually only in terms of PW and PRI. Main drawbacks, although state of the art at the time, were: only a single emitter could be simulated at a time; limited modulation schemes; limited frequency accuracy/repeatability; coarse frequency resolution; and relatively poor noise performance. Most SUTs of the time used the four-port amplitude comparison technique and so a simple receiver model was used in early simulators to generate the required four RF signals. The introduction of commercially available synthesised signal generators improved this situation, but overall the capability was very limited compared to today's simulators.

In the 1970s the only commercially available multi-channel simulator was believed to be the Antekna Standard Threat Emitter System, but this too was similarly based. In 1977 the US Naval Research Laboratories started development, in conjunction with Amherst Systems Inc (which was founded in 1975) of the Tactical EW Environment Simulator (TEWES). This was the first time-shared, highly multiplexed, dense environment simulator. The first production TEWES unit was delivered in 1980, TEWES technology was formally transitioned to industry in 1981 and was developed into the 1983 Advanced TEWES – the forerunner of the CEESIM first delivered by Amherst that year.

EW receiver manufacturers have generally developed bespoke single and multi-source simulators based around the above basic building blocks to support internal product design and development processes. Little information was and is openly published on the capabilities of these bespoke simulators, whose use prevails but has been rapidly supplanted in the last decade by powerful simulators now available.

† P-type – Intrinsic region – N-type semi conductor.

Table 4
Top level cardinal point specification

Top level requirement	Typical range	Comment
Number of platforms and emitters	128-1024 platforms; 128-1024 emitters; up to 1024 simultaneously active emitters *at RF*. Can have many more at digital level, *e.g.* >10k.	Simultaneous emitter capability at RF constrained only by simulator's digital/RF assets; maximum reported capability 8192 but none known in the field with that many simultaneous *at RF*.
RF channels/sources	4-22 channels, usually of mixed types (VCO/DTO/FLO/Synthesiser) and banded in ranges typically 0·5-40GHz, with 0·1-100GHz typical in supplier information.	Modern simulator architectures can cater for up to 64 channels. Synthesisers for CW and High PRF PD emitters.
Pulse density	0·5-8 Mega-Pulses Per Second (MPPS). 1 MPPS = typical all-up pulse density, independent of scenario and RF channel frequency banding. Maximum reported is 8 MPPS.	0·5-1·6 MPPS advertised per RF channel. Average ~0·3 MPPS/channel achieved for real-world emitter scenarios. Pulse 'burst mode' available, giving ≥10 MPPS, but does not represent real world emitter.
RF emitter types & modulations; scan types	All general modulations: Amplitude, Frequency & Phase (AMOP, FMOP, PMOP), Pulse Doppler, hopper (agility), stagger, jitter, bursts, groups, periodic, synchronised. All scan types, including electronically scanned.	High-fidelity intra-pulse modulation for Unintentional Modulation on Pulse (UMOP) – simultaneous AMOP/FMOP/PMOP at 8-12·5ns sample rate.
Pulse Repetition Interval (PRI) & Pulse Width (PW) ranges	PRI: 1 µs - 100ms; PW: 25ns - >32ms	Precision PRI timing now available to simulate individual emitter crystal clocks.
Frequency/amplitude accuracy	Frequency: ±1 MHz (VCO/DTO/FLO); ±5 kHz (synthesised source). Amplitude: ±0·5dB	Frequency accuracy dependent on RF source type and frequency sub-band.
Channel re-tune time	≤1·5µs for DTO/FLO and High-Speed Synthesisers	Channel hop time from one frequency to generate emitter at another, including settling time.
RF output power; noise floor; dynamic range; spurious & harmonics	0 to +10 dBm for direct injection mode, with better than –85 dBm/MHz noise floor. Dynamic range up to 90dB @ 0·25 dB resolution. –60dBc spurious, harmonics and phase noise. Higher (kW) powers using amplifiers, but with increased noise.	Modern, more sensitive SUTs lead to: Lower power outputs (typically –20 dBm) for direct injection, due to Signal-to-Noise Ratio (SNR) trade-off. Pulse-off noise level for direction injection mode better than –100dBm/MHz.
AOA ports, emitter and SUT Rx antenna/aperture modelling	8-50 ports. 0·5-3·0M data points per Rx antenna. ~6k data points per 2D (elliptical) emitter antenna, with 0·25dB amplitude resolution. Dynamic modelling of transmit/Rx polarisation	Ports depends on number of SUT antennas. Instances of >150 ports exist. Rx antenna patterns can be 'calculated' or 'measured.' 3D models now available for emitter antenna patterns (~5M data points per antenna).

3.2 Many-channel simulator suppliers – past and present

Simulators come in a wide range of sizes but, as witnessed by current supplier offerings, there are four main types. 'Pico-' units, e.g. Pico-AMES, are primarily for desktop use; 'Micro-' units, e.g. Micro-Radar Signal Simulator (RSS), are transportable and are well-suited to flight-line use; 'standard' units, e.g. CEESIM-MkN, are full-sized simulators, for laboratory and chamber use; and range simulators. In each case the basic technology is the same, only the capability and price vary. The primary difference between the first three types is the number of RF channels.

In practice, when considering what constitutes a 'many-channel' simulator, there are two main boundaries in laboratory/chamber simulator size for the design and development of modern EW suites – at ≥5 and ≥10 RF channels, independent of source type. Figure 7 shows numbers of channels per simulator for all data currently available to this author.

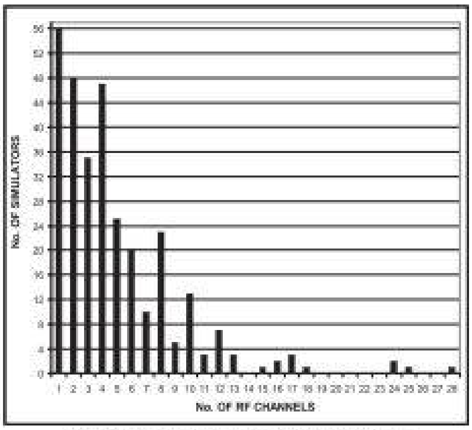

Figure 7. Quantity of RF channels per simulator.

To give the reader a perspective of the scale of many-channel simulators:

- Advanced Dynamic RF Simulator (a CEESIM-MkN), used for laboratory testing the F-22A 'Raptor' aircraft's EW suite, has 6 synthesised RF channels, 156 antenna ports, is 7·3m wide × 2·1m high, weighs 45,500kg and takes 40kVA of prime power.[9]
- That used for laboratory and chamber testing of the Typhoon's EW suite has 11 RF channels.
- The CEESIM capability of the original Benefield Anechoic Facility (BAF), i.e. before its 'Electronic Combat Integrated Test' upgrade, was 22 RF channels.[14]

Over the last two decades there have been few commercial suppliers of simulators, especially of the 'many-channel' type. This author has conducted a number of simulator surveys over the last 21 years and, in conjunction with surveys conducted by the *Journal of Electronic Defence*,[15,16,17] a good picture of the limited number of suppliers of many-channel simulators emerges, see Table 5. This table may be incomplete since not all recipients responded to the surveys. Also, it was determined by this author that some suppliers either did not produce for the open market or only supplied to their own national defence agencies and their contractors.

Some suppliers have either left the market or discontinued simulators since the 1970's, although some types remain in operation. In addition to ownership changes and model retirements indicated in Table 5, such companies and/or simulators have included Marconi Instruments (bought by IFR Systems 1998; sold to Aeroflex 2002); Walmore; PEER (Programmable Electronic Environment Replicator); and Agilent's Frequency Agile Signal Simulator (originally by Hewlett Packard).

4.0 TECHNOLOGY AND PERFORMANCE ENHANCEMENTS

This section discusses changes in simulator technology and performance. Driving requirements are described and enablers outlined. There have been few major technology or performance steps during the past 15 years; rather there has been a continuous and sustained improvement in performance.

Table 5
Many-channel simulators amd suppliers

Supplier	1991-3	1998	2001/2	2006
AAI Corp.	AN/ALM-234 (1986)	AN/ALM-234	X	X
Amherst.,Comptek Amherst.-NGAS Inc.	CEESIM 8k (1991)	CEESIM-8k	CEESIM-MkN (1999)	CEESIM-MkN
ASDI- Comptek, ASD-Comptek Amherst - NGAS Inc.	AMES-II (1985)	AMES-II	AMES-II	AMES-III (2003)
CAL corp.	TASS	X	X	X
Antekna-Intek -Litton-S [3] Inc. -CSA Inc. -Cubic Corp.	X	X	HIDESS	HIDESS
Elettronica	RFEG (AMES-II RF/digital)	RFEG	X	X
Elisra Electronic Systems	X	X	REAS-REGEV	X
EWST (+ EW/ECM ex-Anaren Microwave Ltd.) - Herley Industries Inc.-EWST	RSS7000 & 7500 (both 1993)	RSS7500	RSS 8000 (2001)	RSS8000
Excalibur-DRS EW & Network Systems (Canada) Ltd.	TS-100	TS-100	TS-100	TS-100+
Reflectone UK Ltd.-BAE SYSTEMS-CAE	X	EES600	EES600	X
S.T. Research	RA-600, 600R	X	X	X
Thales - Omega S.A.	X	X	ABYSS	X
Tracor-Marconi Electronic Systems-BAE SYSTEMS	MRES	X	X	X

4.1 Change drivers and enablers

The primary drivers for simulator performance enhancements can be summarised under three headings:

4.1.1 Increasing performance and features of threat radars to be simulated

The overall threat environment, in terms of potential numbers and type of radars, frequency range and distribution, modulation types and CW/pulsed signal density, has grown over the last two decades. Threat radars have evolved during this time, with many new features. This trend is likely to continue to assure radar advantages, whilst being resilient to EW jamming and being increasingly difficult to detect using EW receivers. Simulator-relevant enhancements include expanded frequency range, advanced modulation schemes, electronically scanned (multi-beam) radars and low probability of intercept/detection (LPI/LPD) techniques, e.g. spread spectrum.

4.1.2 Increasing sophistication of EW systems being evaluated

To assist combat survival in modern threat scenarios, EW receiver designs have had to develop to match the above radar developments. This has been reflected in elevated RWR/ESM requirements[1,11,18] such as:

- expanded frequency range from the traditional 2-18GHz to the modern ≤0·5 to ≥40GHz.
- better detection sensitivity (to see threat main-beams and side-lobes at longer ranges).
- more and enhanced measurement and analysis techniques (for improved DF, precision location and ID performance), including:
  - simultaneous phase and amplitude measurement.
  - scan analysis.

  - side-lobe recognition (detection when not in the threat's main beam and detection of LPI/LPD radars).
  - PRI Doppler (fine-grain PRI/frequency shifts as a function of emitter-SUT distance and closing rate).
  - simultaneous horizontal and vertical polarisation detection at the same aperture.
  - measurement of UMOP.
- better handling of dense signal environments, i.e. above the 'rule-of-thumb' 1MPPS threshold.

Generally there has been an upward movement in EW receiver capability that has led to a blurring of the boundary between RWR and ESM, and where, with the sustained rate of technology improvements, high-end ESM capability now approaches ELINT-grade receiver performance. Such improvements have been enabled by extensive and ongoing R&D world-wide on passive sensor technology, DF measurement and ID techniques, digital signal processing and high-speed analogue-to-digital converters.

It is noted that handling a greater number of threats simultaneously is no longer the key performance and cost driver, rather it is a greatly increased diversity of techniques targeting precise geo-location of threats.

4.1.3 The need for increased EW T&E cost-effectiveness

Affordability has always been a key factor for defence customers. In recent times it has become as important as platform and equipment technical performance. The last decade has seen defence ministries driving ever-harder deals with industry – better military product performance at lower cost.[3] During this period there has, in a number of countries, been a transition from cost-plus contracts to fixed price, installed performance demonstration contracts with strict performance verification and acceptance criteria. There has also long been the need to significantly reduce the historically poor schedule, cost and risk performance of EW programmes world-wide. As T&E is a significant part of the overall EW budget, a key requirement has thus been to conduct more and better EW T&E with diminishing budgets. Throughout this period simulators have played an increasing role in enabling much of the required SUT performance to be proven in the laboratory and chamber, rather than by expensive flight test.

With the continuing drive for cost-effectiveness, against a backdrop of tighter national defence budgets, comes a need for better threat simulation fidelity, to enable closer correlation between tests in the laboratory, anechoic chamber, open air test sites, OARs and combat operations. This would enable optimum EW T&E cost-effectiveness.

Another important facet has been the move from customers considering primarily the initial purchase cost in selecting a platform (and hence EW equipment), with less emphasis on running costs, to making that decision holistically, based on 'life cycle cost' (LCC) considerations.

4.1.4 Enabling advances

The core simulator technologies of digital processing, RF signal generation and computing power have, over the years and to a large degree, kept pace with the above challenging requirements. The main technology benefit to simulators during the 15 years has been the reduction in semi-conductor component size, which has enabled a sustained and continuing increase in computing power and faster switching/clocking times for digital/RF components. Figure 8 indicates this continuing trend.

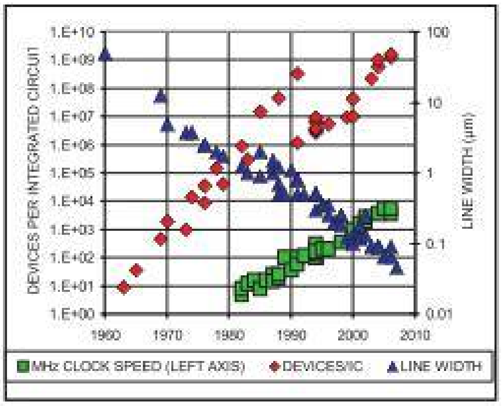

Figure 8. Circuit technology trends.

4.2 Enhancement descriptions

The main enhancements of the last 15 years are now described. Not all capabilities are available in all simulator types and models, although most are now available in larger simulators, e.g. CEESIM-MkN, see Fig. 1, RSS8000† and AMES-III, see Fig. 9.

This author is most familiar with the CEESIM and AMES products, more so with the former, to whose development he has contributed for more than a decade. Whilst the remainder of this section is largely generic, the reader may thus find some bias toward the CEESIM, which is arguably the best known example of simulator technology evolution over the last 30 years. The CEESIM has a solid history, with first of model deliveries after the 1983 original: -64 (1986), -1000 (1986), -256 (1989), -8k (1991), portable (1996) and -MkN (1999). The AMES line, formerly CEESIM's main competitor, has a similar pedigree: -I (1981), -II (1985) and -III (2003). Together, these three types form the largest community of commercially available simulators, with customers world-wide. Independent of model, RF simulators sold or on order for these types are: CEESIM (155), AMES (135) and RSS (100).

Un-prioritised enhancements are described below under the most relevant one of four headings, covering the three modelling elements in Fig. 4 and 'Other enhancements'.

4.2.1 Emitter modelling

4.2.1.1 Fully complex emitters and environment realism

The earliest simulator requirements for emitter generation comprised merely PW and PRI. Computing power, digital and RF component limitations prevented production of large numbers of fully complex emitters, i.e. with full modelling of all necessary RF parameters. The result was simulators with the capability to generate a few so-called 'foreground' emitters along with larger numbers of 'background' emitters. The latter did not have full parameter space modelling and could have pulses dropped at time of contention with 'foreground' and other 'background' emitters.

Nowadays, many-channel simulators of the type emphasised in this paper can produce up to thousands of fully complex emitters at the digital level. Inevitably, the ability to generate these emitters at RF is limited by the number of channels available, the channel pooling capability and the SUT's sensitivity to dropped pulses. This has

† Radar Signal Simulator model 8000, by EWsT, a Herley Industries Inc. company based at Farnborough, UK.

Figure 9. RSS8000 and AMES-III.

enabled significantly better representations of operational RF emitter environments than before. Pre-defined scenarios and man-in-the-loop scenarios can be run, with pre-scripted threat engagements or ones based on weapon system engagement models within the simulator. It is now also possible to include civilian radar emitters, RF jammers and 'third party tracking', where the emitter tracks another platform in the scenario and the SUT hardly ever or never sees its main beam.

4.2.1.2 RF source improvements

The relatively noisy original VCOs were overtaken by digitally tuned oscillators (DTOs), when SUT improvements enabled them to see noise characteristics of the earlier devices. DTOs have evolved, especially since the advent of SUTs more sensitive to phase noise. Recently, frequency-locked oscillators (FLOs), which are more environmentally stable devices with better frequency accuracy, post-tune drift, residual FM and phase noise, have begun to overtake DTOs. All three source types are able to be quickly (≤1·5μs) tuned to different frequencies within their band of operation — enabling a single source to generate multiple emitters, subject to timing constraints and settling time. However, the lack of phase coherency and relatively poor frequency accuracy renders them unsuitable for accurate simulation of high-PRF Pulse Doppler (PD) radars and CW emitters.

Synthesised sources, with accuracies of ±5kHz or better are readily available, in 'high-speed' (HSS) and 'slow-tune' (STS) types. HSS's have switching speeds similar to the FLO but are very expensive, particularly as a single such channel is required to simulate *each* PD or CW emitter for the highest level of fidelity. The use of less expensive STS's is now common, but they have lower performance and are less able to simultaneously generate multiple emitters. HSS/STS unfortunately have higher noise floors than their DTO/FLO counterparts; synthesiser noise thus unavoidably dominates simulator noise performance. Modern sources can suppress harmonics, spurious signals, inter-modulation products and AM sidebands to below –60dBc.

With increased SUT emphasis in recent times on detection and correct identification of emitters at longer ranges, to aid survival and mission effectiveness, there has been greater need for testing at lower power levels than at higher ones. This has led manufacturers of all source types to improve their noise floor performance. Due to dynamic range and SNR considerations, this has also led to a general trend toward –10 to –20dBm for simulators for laboratory testing of modern EW receiver systems, rather than the previous –5 to +10dBm.

To enable users to obtain simulators that are able to fully exercise the signal densities of EW receivers by test, rather than by the commonly used technique of extrapolated test results via prediction or modelling, there is a need for cheaper RF sources of all types. R&D targeting this goal is understood to be in progress.

Until recently source performance and cost has meant multiple sub-banded channels to cover a wide frequency range. Technology advances and LCC improvements have made wide-band sources of all types viable, e.g. 0·5-18GHz, 2-18GHz, with the additional benefit of better scenario generation flexibility.

4.2.1.3 RF pulse shaping

The RF sources listed above have the fundamental limitation that pulses generated are essentially square-wave, see Fig. 10. Real radar pulses, themselves rarely rectangular, can bear little resemblance to square waveforms when they arrive at the SUT's antennas, having been distorted by atmospheric, multipath and SUT platform-specific effects. A key SUT capability is discrimination of pulse start/stop times and peak power. For received real-world radar pulses this is never trivial. SUTs use various methods to optimise their ability in this regard and do not always use the traditional 3dB (half-power) points on a pulse for its start and stop times. Despite this limitation, for most EW receiver systems, the sources used have traditionally provided adequate simulation for T&E.

Within the last decade there have been significant developments in simulator capability to better simulate radar waveforms. The use of synthesiser-based high-fidelity intra-pulse modulation (HFIM) is now well established and yields simultaneous FMOP/AMOP/PMOP for T&E of SUTs with specific emitter identification (SEI)-type capabilities[19]. These SUTs generally work by simultaneously measuring combinations of frequency, amplitude and phase at a fast rate and then comparing the results with a library of unique characteristics of specific emitters. This process is also known as 'fingerprinting' the radar's actual waveform and is discussed elsewhere, e.g. Sections 3.2 and 4.2 of Ref.1. UMOP (within a radar's pulses) has a number of

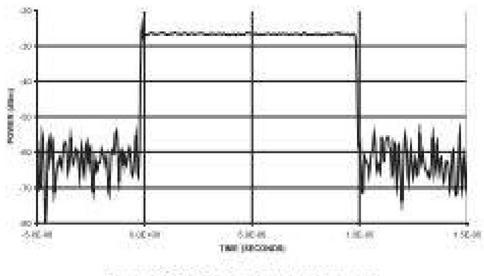

Figure 10. DTO-simulated radar pulse.

causes related to radar source type and maintenance.[20] With the latest technology, UMOP-capable receivers are able to discriminate between radars of the same type having almost identical classical features. Other than a need for faster sampling, the only downside of the above excellent RF sources is their high cost, although research is known to be ongoing into lower cost alternatives.

4.2.1.4 Optimal use of RF resources

An ideal simulator would have many high-speed synthesised channels, each with HFIM capability. Unfortunately, this is currently unaffordable and a compromise has to be made in arriving at an adequate and affordable quantity and mix of RF channel types for a given EW T&E programme.

Given the high cost of all types of RF channels, various methods have been developed for optimising the emitter generation capacity vs. quantity and type of channels, whilst guaranteeing that simulator pulse drop-out does not increase above that which would cause problems to the SUT. This threshold varies in practice, being in the range 3-5%, but this is highly dependent upon the SUT architecture, measurement and pulse de-interleaving techniques used, and analysis software within its receiver and processing elements.

Pulse generation optimisation methods now include:

- channel pooling (pulses in a pulse train can be generated by more than one channel)
- multiple, frequency-dependent receiver thresholds for CW and pulsed signals (RF signals not generated if calculated power below thresholds)
- channel allocation to specific emitter(s)
- prioritisation of emitters and programmable 0-100% pulse drop-out per emitter
- CW fill-in mode, pulse truncation, sector blanking and de-activation/re-activation of emitters

Some methods have driven additional enhancements to constrain artefacts affecting the simulator's output, e.g. tightening of inter-port amplitude accuracy to cover the case where consecutive pulses out of any port can come from different RF channels, to prevent worsening of amplitude accuracy and consequent DF test error budget increase.

Powerful simulator tools now exist, e.g. the environment generation and analysis† (EGA) suite of software models, to enable users to pre-test analyse their test scenarios and SUT features, and thus optimise the RF channel numbers, type mix and frequency sub-banding. Figure 11 gives an example display, showing three emitters, at different frequencies and with different scan periods.

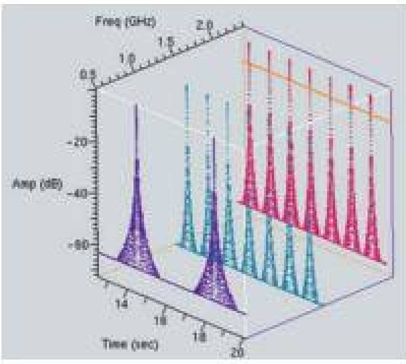

Figure 11. EGA display: 3D environment analysis. (© Northrop Grumman, Amherst systems Inc).

† EGA is a non-real time exact pulse-to-pulse simulation of CEESIM hardware.

4.2.1.5 Modelling of jammers and newer radar features

EW RF simulators, whose primary task is simulation of *radars*, are not *per se* suitable for simulating all types of *jamming* techniques. They are able to simulate some techniques, limited only by the simulator's RF source and modulator performance, but generally have difficulty with noise techniques. Solutions exist, in the form of special channels or adjunct jammer simulation capability, e.g. those by EWST[15].

Most newer radar feature enhancements have been extensions of existing simulator capability, e.g. extended scan rates and angles; track-while-scan (including phased arrays). Simulators can thus now simulate most radar scan types[21]. Other innovations have included complex electronically scanned arrays and crystal clock count-down modelling with separately programmable clock drift rate. This latter relatively recent innovation allows testing of EW systems with the capability to identify a radar from details of its clock and allows simulation of the case where radar signals from radars of the same type on separate platforms 'walk through' each other – a strenuous test for any SUT.

4.2.1.6 Pulse modulator components

Improvements have enabled wider PW range. Faster system clocks and RF component integration have enabled finer resolution for PW (≤4ns) and PRI (better than 0·25ns). Better pulse modulator isolation has led to modulation ratios of >80dB. This ensures that, for most EW receivers and test configurations, pulse-off and inter-pulse signal levels are below the receiver's detection threshold, thus preventing possible false triggering.

4.2.1.7 Emitter antenna pattern modelling

Early simulators had coarse emitter antenna pattern modelling, known as 'key-hole', based on concentric circles of antenna gain. The user would describe the pattern by defining an azimuth range for each antenna gain value and build the elevation view by describing multiple azimuth cuts. For over a decade the much better approach of describing each antenna in terms of a single polarisation elliptical (2D) pattern, with gain *vs* azimuth and elevation cuts, has been common. Computing power limitations until recently have imposed a practical limit on the total number of data points per transmit antenna pattern, e.g. *ca.*7k points, and the simulator's ability to adequately process them at an appropriate rate. This rate can be at each geometry update, at the frame rate (AMES-III) or at the optimal pulse-to-pulse rate (CEESIM).

The T&E workaround for this has been to densely cluster available data point in the boresight region and less so over the remainder of the sphere about the antenna centre. Whilst this has sufficed for verification tests over many years, it is a major limitation in the quest to provide laboratory and chamber simulation that matches flight test/trials results.

More recent developments have included automatic interpolation between data points input by the user and the development of antenna pattern models using a 3D method. These use *ca.*5M data points per pattern and are much better at accurately generating the RF environment at the SUT's antennas than the 2D method, which is not well suited to antennas with irregularly shaped antenna patterns. Unfortunately, computing power and hardware has not yet evolved enough to allow all emitters in a complex scenario to be modelled using this 3D method. Equally important, when simulating newer radars, is the ability to allow fine angular resolution close to boresight for accurate modelling of the very narrow beamwidths now possible.

Further developments are required in this critical simulation area, including better modelling of real-world antenna systems, e.g. radiation spillover, which allows radiation at angles well outside the normal sidelobes, and random polarisation in sidelobes. Figure 12 gives an example of a radar's radiation pattern showing the spillover effect.

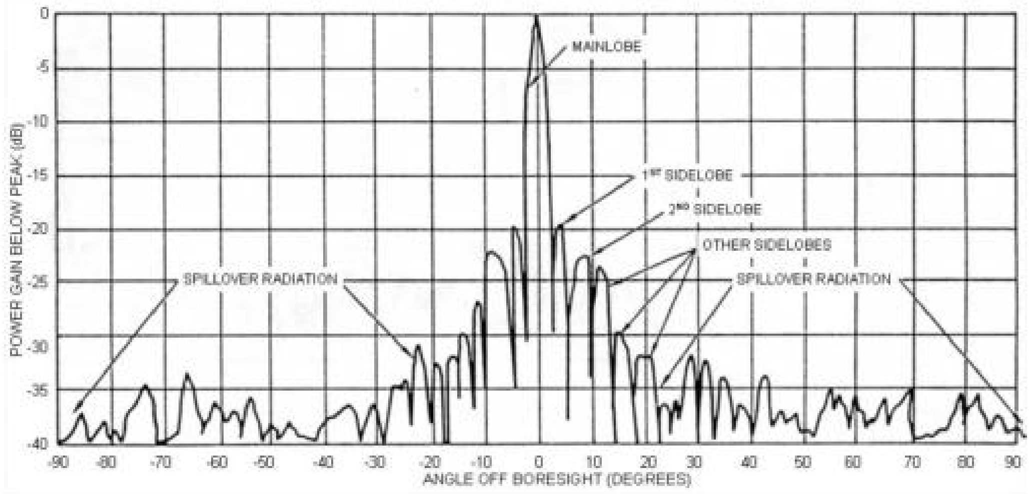

Figure 12. Spillover example (*after Benford & Swegle*).

4.2.2 Propagation and atmospheric effects models

4.2.2.1 Atmospheric effects

The earliest simulators used only a basic radar range equation[19], assuming dry air at Standard Temperature and Pressure, resulting in a path loss L as a function of distance r given by:

$$L = 20\log_{10} r \text{ dB} \quad \text{. . . (1)}$$

In due course the Friis standard radar range equation was used:

$$L = 32{\cdot}44 + 21\log_{10} r + 21\log_{10} f \text{ dB} \quad \text{. . . (2)}$$

where

r = range between transmitting and receiving antennas in km

f = frequency in MHz

32·44 dB is a constant relating distance in km and frequency in MHz

Enhancements then included frequency dependency due to oxygen and water vapour absorption, and scattering due to rainfall rates. Atmospheric ducting, i.e. refractive layers of air, usually above sea, that allow electromagnetic radiation to travel much further than would be the case in dry air, was generally introduced around a decade ago. The underpinning models used are well established, e.g. Skolnik[21] (radar handbook), Van Vleck, also in Ref. 21 (atmospheric absorption), and Kahan and Echart[22] (ducting).

4.2.2.2 Multipath

Specular reflections of emitter signals from the ground/sea and other platforms to the SUT, that simulator computing power limitations previously prevented, can now be modelled. Using parameters including path length difference, graze angle, surface roughness and emitter frequency, the phase angle difference can be determined. Phase angle and modulation amplitude are then used to determine signal attenuation/cancellation or amplification at the SUT antennas.

4.2.2.3 Gaming volume, surface types, terrain modelling/masking

Originally simulators could only simulate flat earth. An early innovation was the additional choice of areas of the earth, up to a few hundreds of km on side. For some time, simulators have been able to generate gaming volumes of between 1k × 1k nautical miles up to entire earth × 100k feet altitude. The World Geodetic Survey 1984 '4/3 spheroid' earth is generally used. In a parallel development, different surface types were introduced – land sub-types and sea states, with either the whole scenario gaming area at one surface type or using reflectivity maps.

Fifteen years ago simulators only provided simple maps, showing primary routes and geographical features, and land surface types were limited to one type per scenario. Simulators can now generate multiple sub-types within a gaming area and use map data from high grade sources, e.g. Defense Terrain Elevation Database (–1) for terrain modelling and masking of emitters, and vector maps for scenario displays. Figure 13 shows a typical scenario display.

4.2.2.4 Platform and Emitter geometry modelling and dynamics

To ensure correct AoA of electromagnetic waves impinging on the platform containing the SUT it is necessary to accurately model relative geometry of platform and radiating emitters. Six degrees of freedom is now standard: latitude, longitude, altitude, roll, pitch and yaw for spherical earth modelling, and x, y, z, pitch, roll and yaw for flat earth modelling.

For adequate testing of EW systems' ability to track threats under manoeuvring conditions, relative geometry needs to be calculated at an appropriate rate. At minimum this tended to be 1Hz in earlier times, which was adequate for a less manoeuvrable aircraft with a coarse DF, azimuth-only RWR approaching a ground-based threat radar. This rate is inadequate for the case where threat and own platform are highly agile fighters and/or the own platform has an EW receiver with high accuracy azimuth and elevation DF capability. Geometry updates should ideally be processed on a pulse-by-pulse basis for maximum accuracy, although no problems have been openly reported once a rate of at least that of the host platform's avionics databus is used. 50-250Hz is common nowadays, with cases up to 1kHz.

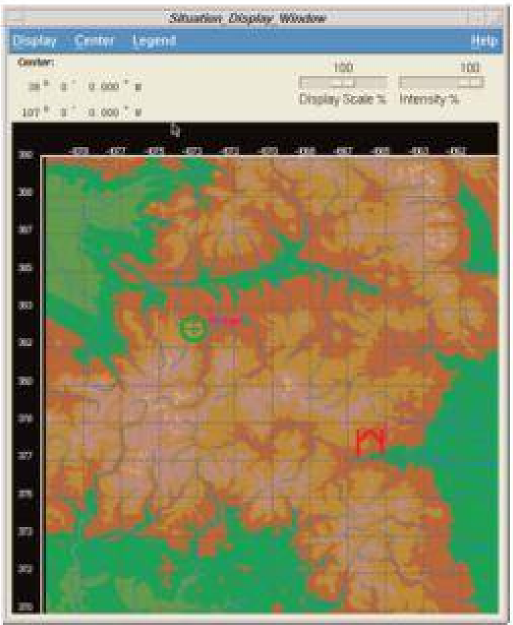

Figure 13. Typical scenario display.
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4.2.3 Platform and SUT antenna/aperture/receiver models

4.2.3.1 Receiver antenna pattern modelling

When a threat or other RF emitter signal impinges on a platform, each of the SUT's antennas is excited by a different power level, waveshape and other signal parameters, dependent upon installation details – primarily location on the platform and pointing direction. Thus the RF response, in phase and amplitude, is measurably different between each antenna element. The SUT receiver and processing elements attempt to take these installation-unique aspects into account when measuring the inbound signal, so as to minimise errors in the DF technique(s) being employed.

For direct injection testing, each SUT antenna element is modelled within the simulator. Originally this could only be achieved for a small number of antennas and then only by the 'calculated' technique, where an imaginary antenna with a single polarisation is described in terms of a set of data points covering the antenna's azimuth and elevation gains *vs.* frequency. Computing power limitations of early simulators led to far fewer points being available than would be required to adequately describe the spiral antenna seen on most SUTs. T&E workarounds involved clustering points in the frequency/amplitude/pointing angle regions of most importance, e.g. boresight. The original limitation of *ca.*0·5M data points per antenna has recently been resolved via research directed by this author and *ca.*3·0M data points, for a large number of antennas of different types, are now available. In addition, interpolation between available data points is now also available.

More recently, the 'measured' technique has become available in simulators. In this case the individual, un-installed SUT antennas and antenna arrays have their phase and amplitude characteristics measured in an anechoic chamber and these data sets are input to a simulator 'measured data' model. It is superior to the 'calculated' one, although more expensive to construct. Individual polarisation responses are modelled for 10's of thousands of measurement points *vs.* vertically and horizontally polarised sources in selected frequency ranges. A good example of this technique was on the F-22A's ALR-94 test programme, where 156 individual antenna elements were so characterised.[9]

4.2.3.2 Digitally controlled attenuators

Switchable attenuators are used primarily for transmit/receive antenna simulation, propagation path modelling and AMOP. Earlier attenuators had at best a resolution of 1dB, which is coarse for environment simulation given the additive accuracy/resolution effects of multiple components. Attenuators improved first to 0·5dB and now 0·25dB is common. Research directed by this author has shown that further improvement to 0·125dB steps would be worthwhile, enabling better representation of real-world signals.

4.2.3.3 Phase comparison and TDOA SUT techniques

Simulators originally worked with early RWRs that only used the relatively simple amplitude comparison technique. The introduction of the phase comparison technique to SUTs to achieve better DF accuracies meant simulators had to provide more ports of RF and with high phase modulation and amplitude accuracies.

The relatively recent introduction of SUT implementations utilising the TDOA technique for improved DF performance required simulators to further tighten phase and amplitude accuracies and added a new dimension – stringent pulse time of arrival (TOA) accuracy and resolution. For example, phase modulation and amplitude accuracies of ±2° and ±0·5dB respectively, and ±1·5ns TOA relative (inter-port) accuracy with 0·5ns resolution can now be achieved.

To enable accurate TDOA antenna modelling it was necessary to introduce a rectangular 'wire grid' model of the platform within the simulator, where each TDOA antenna could be placed at the correct *x/y/z* with respect to SUT 'centre', to a resolution of ≤5mm. Each antenna could then also be inclined/declined in the azimuth/elevation planes (or platform axes), representing required installation angles. Previously this 'centre', where incident power densities were calculated to, represented the co-located antennas of a traditional four-port amplitude comparison RWR installation – often found on an aircraft's tail.

4.2.3.4 Polarisation modelling

Emitter antenna polarisation modelling was originally limited to horizontal or vertical and, in the case of spiral antennas, right hand circularly polarised (CP). Simulators used a simple look-up table of coupling loss between incident electromagnetic wave polarisation and receive antennas of different polarisations, with polarisation mismatch loss fixed per scenario, to determine received power at the SUT. As threat radar technology advanced so did simulators, which introduced additional polarisations and both hands of CP. Table 6 shows a typical look-up table.

A major improvement in this area was the move to full vector modelling of the emitter and SUT, correctly taking into account relative geometry between the SUT platform and the emitters, including the polarisation modification effects of multipath from the ground and other reflectors. Figure 14 depicts orientation mismatch angle modelling. Further developments have included simulation of modern radars with polarisation diversity, i.e. those able to change polarisation on a frame or scan basis.

4.2.4 Other enhancements

4.2.4.1 Simulator control and timing synchronisation

High fidelity testing of modern integrated EW systems necessitates tightly time-synchronised RF stimulus and measurement equipment. For tests

Table 6
Polarisation mismatch look-up table

		WAVE POLARISATION					
		VERTICAL	HORIZONTAL	RIGHT HAND CP	LEFT HAND CP	RIGHT SLANT LINEAR	LEFT SLANT LINEAR
ANTENNA POLARISATION	VERTICAL	0 dB	∞	3 dB	3 dB	3 dB	3 dB
	HORIZONTAL	∞	0 dB	3 dB	3 dB	3 dB	3 dB
	RIGHT HAND CP	3 dB	3 dB	0 dB	∞	3 dB	3 dB
	LEFT HAND CP	3 dB	3 dB	∞	0 dB	3 dB	3 dB
	RIGHT SLANT LINEAR	3 dB	3 dB	3 dB	3 dB	0 dB	∞
	LEFT SLANT LINEAR	3 dB	3 dB	3 dB	3 dB	∞	0 dB

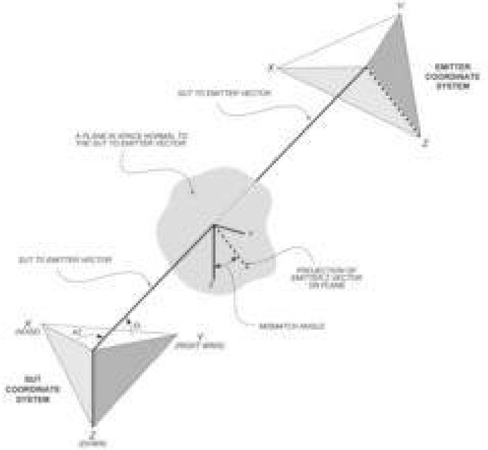

Figure 14. Polarisation mismatch vector modelling.
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where sensor fusion is also to be evaluated it is critical that all SUT sensor stimulators are time-synchronised and controlled by a master test scenario controller. During real time simulations these T&E equipments need to accept precise time synchronisation from a master clock, typically 1-10MHz.

4.2.4.2 Support and analysis tools

Two decades ago much data input was manual, e.g. emitter parameters, transmit/receive antenna patterns and scenario definitions, as was test data analysis. Nowadays the situation is much improved, with features in the latest simulators that ease pre-test tasks and post-test analysis. Examples include:

- User-friendly entry for emitter and SUT-dependent data and scenario development.
- Integrated antenna pattern modelling utilities.
- Simulator recording of 'truth data' for post-test correlation with SUT-measured data, e.g. the CEESIM can record 16 million, 512-bit pulse descriptor words for each scenario run.

The use of adjunct EW T&E capabilities have also been beneficial:

- ECM response measurement systems that are highly integrated with simulators, to measure and analyse RF-level test data.
- High performance data acquisition and simulation systems for stimulating/controlling the platform's avionics (including EW) and simulator, and post-test event-level data analysis.

4.2.4.3 Availability, reliability, spares and life cycle costs

As many-channel simulators are multi-SM complex equipments, it is not surprising that spares packs to keep these items fully operational for the required number of testing hours p.a. are expensive. This is particularly so for the intense use many of them experience. This author has done much fruitful work over the last decade targeting substantial improvements in baseline reliability, availability for testing, fault diagnosis, reduced sparing and lower LCC. Simulators can now use built-in test capability to find and report >95% of faults to the board level without user intervention.

4.2.4.4 Calibration

Emerging EW measurement techniques, especially those for precise geo-location and SEI, place greater technical requirements on simulators – better frequency, amplitude and phase accuracy, and greater stability and repeatability. This has led to greater emphasis on simulator calibration. Unfortunately, calibration times generally increase with increasing SUT measurement technique complexity, although various enhancements have provided some mitigation. The use of vector network analysers for calibrations, rather than power meters alone, is notable and results in halving of times for some calibration types. For SUTs with many antennas this can yield an order better calibration time, e.g. 500 phase ports in ten hours. Despite these enhancements, reducing calibration times remains a challenge.

5.0 SIMULATION FIDELITY – THE QUEST FOR AFFORDABLE EMULATION

This section defines 'fidelity' and other terms relevant to RF threat simulation. It examines how much further up the fidelity curve, as a function of test mission, is worthwhile. The reality of an affordability boundary is discussed and enhancements suggested.

5.1 Definitions

There are many views of the meanings of the terms used to describe how faithful a representation of something is provided by a 'simulation'. Many years ago definitions were relatively straightforward: a simulation could have high or low fidelity. At its highest level of fidelity, the simulation became an emulation of the item concerned. As such it was identical to the item in all respects relevant to the emulation's use.

Nowadays terms such as 'model', 'simulation/simulator', 'emulation/emulator', 'replication/replicate', 'surrogate' and 'hybrid representation' often have multiple meanings, dependent upon nation, agency, technical sector/domain, topic/aspect/item of concern and stage in the platform/equipment life cycle. In some countries references exist to aid clarity of this multiple usage, e.g. Ref. 23, but these are not international standards *per se*.

It is thus necessary to define the meaning of specific terms in the context of this paper:

- ***RF emitter simulation:*** Imitation, at RF, of the real-world characteristics and behaviour of one or more RF emitters, to a given level of fidelity. Note: Simulations/simulators are usually more cost-effective than using real threat weapon system radars for most test missions.
- ***Simulator fidelity:*** The measure of the quality of RF emitter simulation when compared to the real emitter, for all those

spectral, spatial and temporal aspects relevant to the simulator's use in EW T&E.

- ***Emulation:*** Highest fidelity simulation, where a perfect EW receiver could not discriminate between the emulation and the real emitter. Note: Emulations/emulators are useful where the use of the real item is either not necessary or is undesirable.
- ***Verification:*** The process of determining that an EW receiver system, when tested using a threat simulator incorporating threat emitter models, meets its contractual specification.
- ***Validation:*** The process of determining whether the:
  - simulator's output, when programmed with threat emitter models, is adequate for its intended use in the T&E process.
  - SUT, when programmed with theatre-specific Mission Data, correctly identifies and reacts to real/simulated threat emitters
- ***Accreditation:*** The process of determining whether a simulator's rendition of threat emitters is suitably realistic, robust and credible.

5.2 Threat simulation fidelity

Threat simulation fidelity is dominated by two factors – threat emitter characteristics programmed into a simulator and the simulator's capability to translate those characteristics into a faithful representation of the RF signals that would be received by the SUT's antennas when radiated by the real threat under combat conditions. As with any simulation, a threat simulator's capabilities need to be fully understood in terms of the verification, validation and accreditation (VV&A) processes for modelling and simulation,[23] and for SUT performance verification and validation. Table 7 depicts VV&A from a threat simulator standpoint.

Various methods are used to confirm (or 'validate') the fidelity of a simulator's rendition of threats. National methods vary but the US one, described in Ref.24, is a good example. CROSSBOW (Construction of a Radar to Operationally Simulate Signals Believed to Originate Worldwide) is a tri-service technical agency established for the common development of EW RF simulators. It assures that simulators and models are consistent with intelligence agency threat estimates and that validation procedures are being followed. It then certifies simulator-model combinations for use for specific EW T&E cases via accreditation tests. It is understood that full CROSSBOW accreditation for a single threat-simulator combination can take over 12 months to achieve.

5.3 Why better fidelity?

For over two decades the EW community has sought simulators that could provide perfect simulation of the RF emitter environment the SUT sees during combat operations. Emitter data, emitter modelling and RF source limitations currently mean that laboratory and chamber testing remains limited when testing SUTs programmed with theatre-specific mission data.[6]

Efforts are known to be ongoing to close this fidelity gap and thus provide a capability that could enable optimisation of SUT mission data and countermeasures (technical equipment and tactics), maximise the transfer of EW T&E tasks from flight to the more cost-effective and repeatable laboratory and chamber, enhance mission rehearsal capability and shorten resolution times for operational problems. In turn, these would aid maximise platform survivability against RF-guided threat systems and hence improve mission success potential and aircrew life expectancy. Also, even though simulators are much improved, further improved fidelity is increasingly important with shrinking defence budgets, to aid more cost-effective EW systems' development and in-service support.

A good example of these efforts is the correlation of OAR emitters against the CEESIM simulators[25] in the BAF. RF signals from OAR emitters were measured and compared with RF waveforms from the simulators when programmed by the traditional input of parametric data from an EW emitter database, *cf.* Ref.6 Some significant fidelity differences were noted and methods of programming the CEESIM to produce much better representations of the emitters were developed and evaluated. Fidelity enhancements included modelling of radar switching transients, additional intra-pulse modulations and unexpected anomalous behaviours. Correlation of a single emitter took one-to-four months and it was planned to continue the effort whilst feeding back information to the EW emitter database owners to aid refinement for all users.

It was noted that the desired fidelity enhancements were taxing the CEESIM performance capabilities, which is in agreement with the message of this paper concerning all state-of-the-art simulator types, and that enhancement efforts were in progress. As with this paper, the authors of Ref.25 recognised the need to balance the value of increasing simulation fidelity further against the cost of doing so. One of their conclusions for a later phase of work was to gather fidelity requirement inputs from customers, to minimise the risk of over- or under-specifying threat simulation fidelity.

5.4 The affordability boundary

It has been long recognised that achieving emulation of combat air RF environments using simulators is utopian. The combination of

Table 7
Threat simulators and VV&A

PROCESS NAME	OBJECTIVES	KEY QUESTION	PROCESS ACHIEVES	DONE BY
VERIFICATION	USE SIMULATOR TO CONFIRM THAT SUT MEETS ITS SPECIFICATION	WAS SUT BUILT CORRECTLY?	TESTS **FUNCTION & PERFORMANCE**	SUT SUPPLIER & PLATFORM/SYSTEMS INTEGRATOR
VALIDATION	CONFIRMATION THAT: 1. SIMULATOR PRODUCES ADEQUATE REPRESENTATION OF EMITTERS 2. SUT, WHEN PROGRAMMED WITH THEATRE-SPECIFIC MISSION DATA, CORRECTLY IDENTIFIES SIMULATOR-GENERATED EMITTERS	DO SIMULATOR-GENERATED EMITTERS LOOK & BEHAVE SUFFICIENTLY LIKE THE REAL THING?	EVALUATES **FIDELITY**	MILITARY, OFTEN WITH INDUSTRY SUPPORT
ACCREDITATION	CERTIFICATION THAT [SIMULATOR + THREAT EMITTER DATA] IS ADEQUATE FOR PROVING [SUT + MISSION DATA] IS FIT FOR INTENDED MILITARY PURPOSE	CAN SIMULATOR BE USED TO OPTIMISE & VALIDATE MISSION DATA FOR EW RECEIVER SYSTEMS?	DETERMINES **CREDIBILITY**	MILITARY, OFTEN WITH INDUSTRY SUPPORT

affordability, highly complex electromagnetic interactions experienced in the real world and simulator technology limitations is likely to constrain simulations to limited resemblance to the high-pulse density, confusing electromagnetic 'mush' that is often the electronic battlespace in modern conflicts.

However, with reference to the definitions above, a *perfect* EW receiver is unlikely to ever exist. Thus the question is really whether a simulator provides sufficient fidelity for the SUT to be unable to discriminate between its outputs and emitters in the real-world RF environment. This, as for other areas of avionics T&E, is a question of adequacy – there is no need to generate significantly better fidelity than the SUT can measure. In terms of adequacy, there are a number of rules of thumb that suggest T&E equipment should be able to simulate/generate/measure to an order better than the SUT can measure. Whilst often possible in the digital context, this is less easy in the RF world but modern simulators can, for most parameters, easily exceed the parameter range of the SUT. It is less easy, even given today's technology, to significantly improve on parameter accuracies and resolutions, though few problems have been reported in this area.

When using the best available emitter simulation features described in this paper, most current SUTs – when programmed with appropriate emitter libraries and other mission-dependent data – are unlikely to be able to discriminate between the simulator's outputs and those of a real emitter. However, this statement is usually only true for low numbers of emitters and limited signal densities due to simulator affordability constraints on the number and types of RF channels available. Whether it is true for operationally realistic emitter numbers and (higher) signal densities cannot be determined practically without adding further channels of the necessary type or flight testing against an OAR with the necessary assets. RF output power constraints, again an affordability constraint for laboratory and chamber testing, can likewise limit the scope of simulations.

Despite significant improvements in simulator capability to stimulate SUTs using the TDOA technique, there remains an issue for simultaneous intra-pulse modulation and TDOA, *cf.* Ref.18 Without the use of HFIM in each RF line to the SUT's antennas, it is currently not possible to faithfully model the RF environment for that case. Unfortunately, the technology solution is available, but in practice is unaffordable. Fortunately, for some SUTs this is not an issue and for others a T&E workaround can be effected that, although restrictive, appears adequate for performance verification tests. It is thought that upcoming receivers, including enhanced 'digital receivers', will be less tolerant of this limitation.

The latest simulator technology and capabilities, particularly when enhanced in line with the outcome of the BAF efforts reported in Ref. 25, appear to be at the fidelity level where more of the T&E currently done by flight testing against real threat emitters could to be executed within the anechoic chamber and laboratory environment – offering cost saving, repeatability and investigation benefits. In addition, were the more important suggested developments of Section 5.5 realised, then it is considered that an increase in RWR/ESM/ECM mission data validation quality could also be achieved, with attendant survivability benefit to platform and aircrew. Once the above simulation fidelity level has been realised, the need for any further fidelity increase will need to be cost-benefit traded to determine whether the required tests might be better conducted *via* OAR flight trials. This situation is also in line with the US Defense Modeling and Simulation Office's view on *'State of the Art in Fidelity'*.[26]

5.5 Suggested further developments

The following suggested developments, most of which are discussed earlier, are considered worthwhile. They are in addition to, but may overlap with, those resulting from efforts reported in Ref.25. Some are of greater importance to EW T&E in the near future, should the enhanced detection, DF and ID capability promises of 'digital receivers' be fully realised.

- Better transmit antenna models, including radiation spillover, random polarisation in sidelobes and appropriate interpolation between data input by the user.
- Improved multipath modelling, including that for pulse stretching and reflections from other platforms.
- Faster HFIM channels.
- Affordable solutions to limitations on intra-pulse simulation for testing SUTs that employ the TDOA technique.
- Improved noise performance synthesised RF sources (this is particularly important for multi-channel simulators used for testing SUTs with very high detection sensitivities).
- Increased parameter ranges.
- Improved calibration capabilities, reliability and fault diagnostics to aid users maximise simulator time available for testing and minimise life cycle costs.
- Enhanced pre-/post-test analysis tools.

Some of the required technologies exist for shortfalls identified in this paper, although most are either not yet 'in the field' or commonly available, due to implementation cost and/or lack of customer/user request. For example higher resolution digitally controlled attenuators than the currently common 0·125dB ones would enable usefully improved transmit antenna modelling and AMOP. 0·1dB attenuators exist, but the changeover costs for an established simulator product are appreciable.

One fidelity enhancement considered worthy of further investigation is the inclusion of own-platform effects within simulators. Installation-unique multipath and scattering of inbound electromagnetic waves prior to being converted by SUT antennas into RF current into EW receivers is not well understood. These effects are known to be highly specific to platform type, with some specific to individual platforms within the type. Effects include pulse attenuation/amplification, wave-shape distortion and polarisation changes. Some aspects have been captured *via* installed antenna/aperture modelling, but a 'platform-specific' component remains unknown.

A way ahead may be adoption of surface models used for electromagnetic compatibility, lightning strike and communications antennas' installed performance modelling, e.g. Fig. 15. The challenge would be the real-time modelling of simulated antennas positioned on a surface model with mesh sizes as small as 0·3mm (wavelength/25) for EW frequencies.

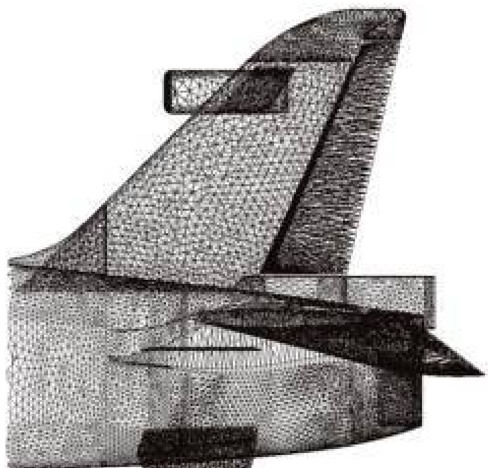

Figure 15. Typical aircraft surface model.
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6.0 CONCLUSIONS

- RF threat simulators are essential to reduce time and expense in developing, integrating, evaluating and supporting ESM/ECM receiver and processor systems. Their use is crucial if operational performance is to be assured, mission success potential maximised and survivability optimised.
- Simulator technology has significantly matured over the past 15 years. Increases in computing power, in particular, have helped overcome earlier limitations. High fidelity simulation of operationally realistic RF scenarios is now possible, although multi-$M expensive.
- Simulators have enabled a major shift from expensive and hard to repeat development flight testing and military flight trials to repeatable and cost-effective anechoic chamber and laboratory testing. For the foreseeable future they will continue to be a powerful enabler for this ongoing transition.
- Technology mostly exists to enable emulation (perfect simulation) of RF environments seen in military operations, but this is not currently feasible. Key obstacles are:
  - Affordability, including LCC.
  - Sub-optimal models of emitter and SUT antennas, and other RF emitter characteristics.
  - Lack of suitable real-time 0·5-40GHz electromagnetic models of own-ship and other platforms for use in simulators.
  - The confounding complication of hostile, friendly and own RF jammers.
- It is thus considered unlikely that modelling and laboratory testing will ever totally supplant the need for 'installed performance' platform testing in anechoic chambers and flight.
- The high cost of emulation, if possible, is not warranted for all test missions as the current combination of modelling, laboratory and chamber tests using simulators, and flight trials against OAR assets (real and 'emulators') can provide good pre-combat confidence in EW systems' performance and effectiveness.
- With shrinking defence budgets and increasing EW system complexity, however, further improved fidelity is increasingly important to aid more cost-effective EW systems' development and in-service support.
- Developments are suggested that will also help maximise the amount of EW T&E that can be done more cost-effectively in the chamber and laboratory than in flight. Selected items could also improve mission data validation quality and hence survivability.
- Affordable simulation is very much a return-on-investment trade that should be taken at the product life-cycle level. A high-fidelity, many-channel simulator is truly a huge investment, but as it reduces live testing with the fielded platform and remains in productive use over many years, payback occurs quickly.

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A question of survival – military aircraft *vs* the electromagnetic environment

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ABSTRACT

Military aircraft, by definition, need to survive the onslaught of opposing forces to successfully complete their mission. From an aircraft perspective, the electromagnetic (EM) environment can be an enabler, via the use of navigation aids, radar, radio communications etc. – in fact mission success depends on its successful use. However, this environment is also potentially a disabler, as threat weapon systems and the environment itself can harm or destroy the aircraft. This paper discusses risks and hazards thus posed to aircraft survivability, partitioned into two classes – 'direct' and 'indirect' EM threats. 'Direct' threats are those that occur as a result of direct coupling of EM energy to the airframe and systems within, e.g. lightning strike and directed energy weapons. 'Indirect' threats are those that utilise EM sensors to detect, track and target the aircraft, e.g. radar-guided surface-to-air missiles. Airframe intrinsic mechanical vulnerability is also an important part of survivability, although not addressed in this EM-related paper. It is shown that risk and hazard can be minimised by gaining a thorough understanding of operational scenarios, developing holistic system-of-systems solutions to military requirements, and using best practice design and development techniques.

NOMENCLATURE

AAA	anti-aircraft artillery
AAM	air-to-air missile
AN/AAQ-24	US equipment nomenclature for 'NEMESIS' DIRCM
CEESIM	combat electromagnetic environment simulator
CHAFF	chopped aluminium foil
CNN	Cable News Network
DAS	defensive aids system/suite
DEF STAN	defence standard
DEW	directed energy weapon
DIRCM	directed IR counter measures
EM, EMC	electromagnetic, EM compatibility
EMCON	emissions control
EMH, EMI	EM hazards, EM interference
ELINT	electronic intelligence
EO	electro-optic
ESM	electronic support measures
EW, EWTF	electronic warfare, EW test facility
HPM	high power microwave
IADS	integrated air defence system
IR, IRS	infra-red, IR signature
MANPADS	man-portable air defence system
MIL STD	military standard
MIRGAT	mobile IR ground-to-air tracker
NATO	North Atlantic Treaty Organisation
NEMP	nuclear EM pulse
NNEMP	non-nuclear EMP
P_k	probability of kill
PSO	peace support operations
RCS	radar cross section
RF, RFI	radio/radar frequency, RF interference
SAM	surface-to-air missile
SA-[number]	NATO type or designation of SAM
SEAD	suppression of enemy air defences
T&E	Test and evaluation
UAV	unmanned/uninhabited air vehicle

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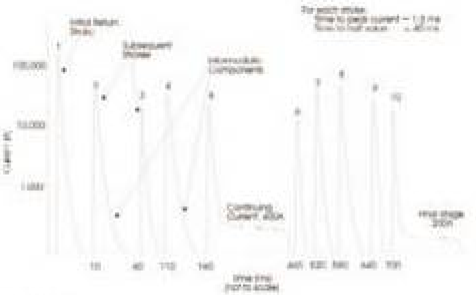

from ARP 5412

Figure 1. Lightning strike waveform.

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Figure 2. AN/AAQ-24 'NEMESIS' DIRCM transmitter.

1.0 INTRODUCTION

Military aircraft, whether fixed or rotary wing (helicopters), are an essential part of modern conflicts. They come in many shapes and sizes, from 10m wingspan fighters to transport aircraft such as the ubiquitous C-130 Hercules and 52m wingspan C-17A 'Globemaster'. They enable the projection of air power, which is a major factor in winning battles, campaigns and wars. Numerous conflicts since World War 2, e.g. the two Gulf Wars, Bosnia, Kosovo and Afghanistan campaigns, and the ongoing international war against terrorism, underline the need for capable and survivable military aircraft.

Victory in modern conflicts usually goes to the side who establishes air superiority first and maintains it the longest. Unfortunately for military planners, air power is a time-dependent variable. Ideally, one should have sufficient air power to gain air supremacy over the whole conflict zone and retain it for the campaign duration, such that land, naval and air forces can operate against the enemy with impunity. Air superiority, on the other hand, is easier to attain but is usually localised, time-limited and means that enemy air forces still pose a threat to own and friendly forces.

To ensure military success, aircraft survivability must be maximised, by minimising risk of attack and resultant damage and loss (attrition). Survivability, a reasonably well understood topic[1], is defined as the measure of an aircraft's (or system's) tolerance and persistence within a given environment. In the military context it comprises battle damage avoidance, tolerance and repair. Experience also shows that victory invariably goes to the side who manages to keep the higher number of its aircraft serviceable and capable of re-arming and returning to battle. Two further important and complicating aspects exist:

- Affordability – defence ministries world-wide have to achieve ever-increasing value for money and invariably require industry to achieve the above with minimum initial and overall life cycle costs. These ministries and their air forces also generally require more and better functionality and performance in the aircraft and weapon systems they purchase, than previously.
- Stringent rules of engagement apply to operations, especially so for peace support operations (PSO), to prevent civilian casualties and loss of own aircraft or aircrew. This is increasingly important in a world where often fragile multi-nation coalitions, operating under NATO, United Nations or other auspices, can be easily shattered by the loss of political will resulting from the loss of coalition aircraft – especially when personnel are captured or killed. Thus the goal of 'zero attrition' has evolved, especially during PSO.

Against this complex and challenging background, the EM environment, also known as the 'electromagnetic battlespace', poses but one set of hazards to aircraft survivability. This paper provides an insight into military aircraft survivability by discussing these hazards, partitioned into 'direct' threats, e.g. lightning strike and directed energy weapons (DEW); and 'indirect' threats, e.g. radar-guided surface-to-air missiles (SAM's). The exposure of an aircraft to direct and indirect threats depends on a number of variables, including aircraft type, role, mission, theatre of operations (geographic location), weather and military conditions (peacetime, transition-to-war, war and 'operations other than war'). It is worth noting that most issues apply also to military naval and land vehicles, and to civilian aircraft and ships during peacetime. Whilst airframe intrinsic mechanical vulnerability to damage or destruction is an important part of survivability, it is not specifically addressed in this EM-related paper. Finally, it must be remembered that survivability is not enough in its own right, we must survive to fight and not just fight to survive.

2.0 'DIRECT' EM THREATS – THE NATURAL AND MAN-MADE ENVIRONMENT

Direct threats, which are covered under the umbrella of EM Hazards (EMH), are outlined below. It is important to recognise that there are no surprises here – given a high enough EM power density or field strength, any technological or biological system can be upset.

2.1 The radio and radar frequency (RF) environment

The RF environment is defined by field strength vs. frequency, in the range 0-300GHz, at the aircraft's position as it flies through the atmosphere. It is the summation of RF fields from all military and civilian telecommunications, radars and other RF transmitters, including those located on the aircraft itself. This environment exists during times of peace and war, although environment complexity is usually higher during war (when most military transmitters are utilised), As many RF transmitters utilise a scanned beam to cover the area of interest and employ pulsed RF waveforms, the aircraft-incident field strength from any given emitter is highly probabilistic. For example, if an aircraft flies past an air traffic control radar which uses a typical ten second rotation period, then the aircraft may only 'see' a few pulses and then not all at main-beam field strength. On the other hand, an aircraft flying past a SAM tracking radar will see pulses continuously and field strength will increase to the nearest fly-by distance, then decrease as the aircraft flies past.

2.2 Special case contributors to the RF environment

These comprise lightning strike, nuclear EM pulse (NEMP) and RF DEW, comprising non-nuclear EM Pulse (NNEMP) and high power microwave (HPM). Lightning strike, in its most threatening form, places the aircraft as part of the lightning channel, driving an extremely high current (50-200kA), complex voltage/current waveform through the structure and hence through the system. The phenomenon is reasonably well understood and there are specifications[2] that describe the rise time and complex waveform, see Fig. 1, which yield a spectral content from a few kHz to 50MHz. A lightning attachment to an aircraft poses three distinct hazards:

- Physical damage at the attachment points.
- High currents flowing on and within the airframe, which can cause damage to mechanical and damage to, or upset of electrical/electronic components.
- A much lower threat can arise from nearby lightning strike causing high EM fields to be propagated toward the aircraft. These fields can cause upset of electrical/electronic systems.

NEMP and NNEMP can be rather different in waveform to lightning strike. These and HPM, are covered in the open press[3,4] and on the internet. It is generally accepted that transmitting arrangements capable of generating DEW-capable, extremely high field strengths exist, albeit some only yet in the laboratory. Operational utility questions persist, as systems capable of generating and projecting appropriately high levels of RF energy at militarily useful ranges remain elusive for a number of significant technological reasons. DEW are subtly different to EW systems, since EW systems primarily utilise a priori knowledge of specific threat weapon systems and their weaknesses, whereas DEW requires only general knowledge of the technology used in those systems and their probable hardness to high EM field strengths – an EM Compatibility (EMC) issue.

2.3 Laser DEW and other optical threats

These reside in the EM spectrum's non-RF bands. However, as currently predominant threats are in the RF and infra-red (IR) sub-bands, only brief comments are made here. Laser DEWs have been in service for some time. Their main use is the dazzle or damage of electro-optic/optical guidance sensors on enemy weapons. Strangely enough, the best-known examples of laser 'DEW' are actually part of an aircraft's self-protection electronic warfare (EW) suite (also called 'defensive aids system' – DAS) – Directed IR Countermeasures (DIRCM) – see Fig. 2.

In DIRCM systems, a low power tracking laser, cued by an aircraft-mounted missile warning system, home onto the head of an inbound IR-guided ('heat seeking') missile. A dazzling, lamp- or laser-based IR source then attempts to jam the missile seeker circuitry and thus cause it to miss the aircraft. Although currently physically large (30cm spherical rotating optical heads), heavy and expensive, ongoing technological, size reduction and affordability advances suggest that DIRCMs are likely to be widely fitted in the future. Other optical threats, e.g. high intensity, non-laser light, can cause pilot dazzle, but are generally not viable against fixed wing aircraft at speed.

Table 1
SAM size and engagement ranges

SAM System	Length (m)	Diameter (m)	Launch mass (kg)	Engagement range (km)
SA-2	10·00	0·50	2,000	50
SA-3	5·95	0·55	953	18
SA-4	8·78	0·86	2,453	55
SA-5	10·80	0·86	7,100	250
SA-6	5·80	0·34	630	24
SA-7	1·44	0·07	10	6
SA-8	3·16	0·21	128	12
SA-9	1·80	0·12	30	7
SA-10	7·25	0·51	1,640	100
SA-11	5·60	0·40	650	28
SA-12	10·00	0·85	4,600	80
SA-13	2·30	0·32	40	8
SA-14	1·42	0·07	10	6
SA-15	3·50	0·35	165	16
SA-16	1·67	0·07	11	7
SA-17	5·60	0·40	715	28
SA-18	1·71	0·07	11	7
SA-19	2·56	0·17	71	10

3.0 'INDIRECT' EM THREATS – MISSILES AND ARTILLERY

3.1 Threat types and capabilities

Indirect threats pose the most serious and prolific hazard to aircraft. SAM's, air-to-air missiles (AAMs) and anti-aircraft artillery (AAA) have only one purpose – aircraft destruction. With CNN-type coverage of military conflicts, this fatal reality is obvious to all. Figure 3 shows typical examples of threat systems, whilst Table 1 indicates typical physical sizes and target engagement ranges.

3.2 Guidance system sensors

Threat guidance systems fall into two categories, dictated by the sensors used:

- RF, i.e. radar rather than radio.
- EO, i.e. IR, ultra-violet (UV), lasers, television and optical instruments. EO sub-types include technologies such as thermal imagers and image intensifiers.

These may be located on the launch vehicle, remotely on another vehicle, on the missile/AAA or on all three. Sensor types used depend primarily upon the required detection range, sensors' location and atmospheric conditions. Multi-spectral or 'dual-mode' guidance is a recent trend, to ensure maximum probability of kill (P_k), even when being jammed in one EM sub-band by the target aircraft's self-protection system. Figure 4 indicates the relative magnitude of the SAM, man-portable air defence system (MANPADS) and AAM threat world-wide against guidance sensor(s) type. This shows that, despite this trend, the single-mode (RF or EO) sensor-based guidance system still predominates. AAA are excluded from this consideration as it is difficult to isolate the precise guidance methods for all the approximately 31 types and 43,000 systems in use. Many are single-sensor on delivery, but often subsequently augmented with other sensors.

Although a variety of sensor sub-types and technologies exist, the threats can be broadly split into IR-guided and RF-guided missiles, and these are discussed below. Whilst both technologies are applicable to AAA also, the remainder of this section discusses only the more hazardous threats – missiles.

Figure 3. Typical SAM, AAM and AAA systems.

Table 2
Mission kill data

Threat	Type	Code-name	Conflict/Era	Combat firings	Kills	% Kill rate
IR-SAM	SA-7a	Grail	Vietnam war (1965-75)	[not available]	[not available]	33
	SA-7b	Grail	Yom Kippur war (1973)	4,356	6	0·14
RF-SAM	SA-2	Guideline	Vietnam war	9,058	150	1·65
	SA-6	Gainful	Yom Kippur war	840	20	2·3
IR-AAM	All AIM-9	Sidewinder	up to January 1990	1,382	308	22·3
	AIM-9	Sidewinder	Iraqi losses in Gulf War 1 (1991)	[not available]	13	[not available]
RF-AAM	AIM-7	Sparrow	1958-1994	654	96	14·7*
	AIM-7	Sparrow	Iraqi losses in Gulf War 1	[not available]	23	[not available]
	AIM-120	AMRAAM	Iraqi losses in Gulf War 1	[not available]	2	[not available]

* Wide variation by conflict: Vietnam 8%, Yom Kippur 33%, Bekaa Valley (1973) 50%, Libya (1982-9) 33% and Gulf War (1991) 62%.

3.3 IR-guided missiles

This is split into two main groups:

- MANPADS, of which the Stinger is a well-known type (Fig. 3), are a serious threat to low-altitude operations, being difficult to detect and counter, easy to use, lightweight and relatively cheap with widespread availability. Over a million MANPADS missiles of various types have been produced world-wide, by over 20 countries. The current inventory (after firing, end-life and monitored destruction) is difficult to predict but has been estimated at over 500,000[7].
- Vehicle-mounted IR SAM and AAM systems, with many examples of tracked-vehicle, aircraft- and ship-borne implementations in existence, e.g. SA-13 Gopher (dual-band IR tracker). Recent innovations include addition of complementary EO tracking systems to RF-guided AAA/SAM systems, e.g. the 2S6/SA-19 system (see Fig. 5), resulting in a more lethal, multi-spectral threat.

3.4 RF-guided missiles

Originating pre-1960, these have been used in most conflicts and have undergone many enhancements.

- RF SAMs are fixed site or transportable. When operational they are arranged with a number of multiple missile launchers, with separately spaced vehicles for power, missile carriers/re-loaders, radar/EO guidance/tracking and fire control. Some systems, e.g. SA-8 Gecko (Fig. 3) have incorporated most functions into a single tracked vehicle. Many systems have the ability to fire salvoes of missiles seconds apart, with subsequent missile re-load times of a few minutes. Although less mobile than the MANPADS threat, some short and medium range SAM's can be stripped down and be on the move within 30 minutes of firing, e.g. the SA-3 Goa (Fig. 3), making them difficult to detect, locate and destroy.

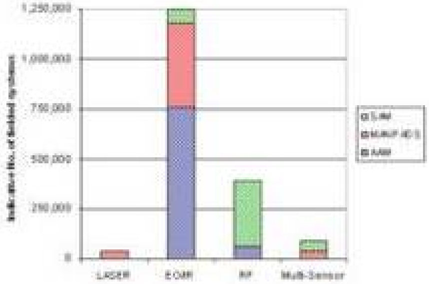

Figure 4. Missile quantities and guidance sensor types.

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Figure 5. 2S6/SA-19 Tunguska RF/EO-guided AAA/SAM system.

- RF AAMs are fewer in number of types than SAM's, but have seen recent impressive performance enhancements:
  - longer range capability and more powerful warheads,
  - better capability against jamming, i.e. electronic counter-countermeasures (now known as electronic protection measures).
  - decreased IR and UV emissions from the missile plume and body, to reduce the target aircraft detecting the missile and being able to engage countermeasures.
  - inclusion of radars in the missile head, yielding the fire-and-forget, so-called 'active seekers', which require no post-firing help from their host aircraft.

3.5 Threat weapon system usage

Threat weapon systems defend a given target location or area. Targets could be airfields, power stations, manufacturing capabilities or military command and control centres. An integrated air defence system (IADS) is usually used, comprising many point defence and zone [sector] defence assets. These assets are the weapons themselves: SAMs, AAA and air defence aircraft with AAM's, combined with long range search and early warning, medium-range search and track, and short-range fire-control radars, linked together by communications systems to a command structure and operations centre.

Often a layered IADS is created, with a target being defended close-in by a large number of shorter range SAMs and AAA, with a number of medium and longer range SAM's located nearby. This satisfies common air defence principles or 'doctrines': forward defence and defence in depth. The two aims are to destroy the attacker as far away as possible from its target and to provide zone-by-zone defence from extreme range down to point defence. Such an IADS means that attacking aircraft face an increasing intensity of attack themselves as they approach the target. CNN coverage of night-time tracer fire over Baghdad during the Gulf Wars exemplifies this end-game intensity.

3.6 Weapon lethality

Many factors affect the success of threat systems when engaging aircraft. These include:

- Altitude: flying high degrades the surface threat's targeting accuracy and, dependent upon weapon engagement range, can prevent the AAA and MANPADS threat from engaging at all. Flying high, however, exposes the aircraft to an increased RF-guided SAM threat.
- Routeing: avoiding the threat altogether – usually not possible for the whole mission and assumes prior knowledge of threat locations.
- Stealthiness, covering radar cross section (RCS), IR Signature (IRS), RF/EO transmissions and optical signatures. These maximise the delay before the threat detects the aircraft, thus limiting the threat's targeting time and thereby reducing the probability of weapon firing and P_k.
- Countermeasure and tactics effectiveness against each threat type: preventing weapon engagement, launch and, in the case of missiles in flight, approach and detonation.

Weapon system P_k is a function of probabilities of targeting, launch, attaining terminal position with respect to the target aircraft, i.e. getting within the 'kill radius', and detonating in a way that the target is disabled or destroyed. Most issues can be visualised, from the viewpoints of SAM operators and the targeted aircraft, from the SAM firing sequence in the George Clooney film *The Peacemaker*.

To put the missile threat into perspective, Table 2 gives open source kill data for a selection of missile types from a number of conflicts. Although simplistic in nature, the table demonstrates that the public's perception that missiles are 'fire-one-kill-one, fire-another-kill-another' weapons is not wholly true. The reality is that each and every engagement is a stochastic event with an uncertain outcome, especially as humans are in the loop in the threat system and the target aircraft. Thus weapon and countermeasure effectiveness, which are each a combination of equipment technical performance and human tactics employed in their use, can be widely different for each engagement. Tactics are often the deciding factor in these live or die situations.

Table 2 also suggests that IR-guided SAMs apparently pose the most significant threat to aircraft. While true in absolute terms, this masks the real situation – that RF-guided threats are generally being adequately countered by the tactics and RF electronic countermeasures ('jammers') utilised on modern aircraft. Were the development of jammers and refinement of tactics to stop today, then RF

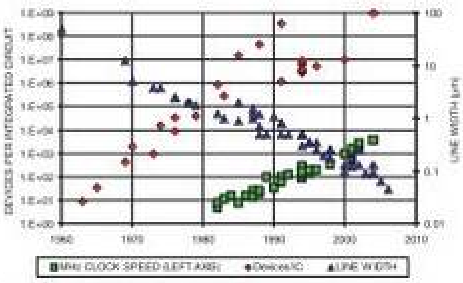

Figure 6. Circuit technology trends.

Table 3
RF Interference Examples

AIRCRAFT	SOURCE	CAUSE/EFFECT
USS *Forrestal*: aircraft carrier	Carrier radar	Poorly shielded plug: Missile fired into other aircraft: 134 dead $72M damage
Black Hawk helicopter	Radar/radio masts	Several crashes attributed to RFI of flight control systems
Various passenger aircraft	Portable devices	24 pilot reports of RFI due to passenger-operated electronic devices
B747-100 Jumbo	Camcorder	Slow left turn
B747-200 Jumbo	2 Laptops	Compass moved 150 degrees
Agusta 109 helicopter	Radio mast	Spurious engine readings, to normal after 7-10 seconds
Various	Radio masts	Spurious readings on GPS

threat developments would eventually overcome them and far more aircraft would be lost thereafter to RF threats. This is the never-ending 'cat-and-mouse' development of threat, countermeasure and counter-countermeasure prevalent in the justifiably secretive world of EW.

3.7 Relative significance of direct and indirect threats

Indirect threats pose a much higher risk than direct ones, even though the latter can also cause mission failure or aircraft loss. To put this into perspective, during combat one is significantly more likely to lose aircraft to SAM/AAM/AAA than to lightning strike. While the actual P_k figures for SAM/AAM/AAA are many and varied, this indicates how more significant the indirect EM threat is in wartime. However, and this is a big reservation in our increasingly litigious society, it is totally unacceptable for aircraft to be brought down by (for example) lightning strike onto a populated area. Thus, especially as military aircraft spend most of their time operating in peaceful airspace, the direct and indirect threats are treated with equal seriousness by aircraft designers and avionics engineers.

4.0 UPSET AND DAMAGE MECHANISMS

4.1 Direct threats

Upset and damage caused by direct threats can generally be ascribed to EM Interference (EMI) in its widest sense, covering RF and optical parts of the EM spectrum. The primary effects seen are jamming of RF sensor systems, upset and damage of electronic circuitry, optical sensor jamming, dazzle or damage, and lightning strike physical damage to the airframe. In each case, EM energy ingress into RF/optical/EO sensor apertures and into the airframe itself is a key factor in upset and damage mechanisms.

It is important to discriminate between upset and damage, as the former can but normally does not significantly impact survivability but may compromise mission success probability, whereas the latter will certainly adversely affect both. With few exceptions, upset is a temporary and recoverable situation on EMI removal, whereas electronic/optical/EO component destruction is not. Upset manifests itself, for example, in systems which cannot be engaged or disengage themselves and cannot be re-engaged, or give a failure indication until the source of EMI is removed or by-passed (which is not difficult when flying). Other indications may be temporary interference on TV displays, akin to RF jamming on early generation radar displays.

There have been many publications covering the topics of susceptibility and protection of electronic circuitry when exposed to high RF fields and currents. Occurrences of EMI (or rather RF Interference – RFI) of aircraft electronics have been reported and Table 3 gives but a few examples.

RFI depends upon a number of RF environment factors, predominantly power density, frequency and waveform characteristics, e.g. pulse width, pulse repetition frequency. The smaller the normal operating signals (including power supplies) the more susceptible they are to upset by RFI, unless adequate shielding or filtering is used. Unfortunately, from an EMC standpoint, the ever-increasing device density per integrated circuit – required for increased computing performance – exacerbates this situation. Fig. 6 shows these circuit technology trends.

It is important to recognise that there is usually a significant power density differential between upset and damage, whether regarding electronic circuitry or (dazzle/damage of) optical/EO sensors by lasers. A typical figure is at least 1,000 times higher for damage than upset, although the actual figure varies widely and is highly dependent upon the specific threat type and electronic or optical/EO device concerned. Figure 7 illustrates this with a summary of RF damage thresholds for a range of electronic components, from Ref. 6.

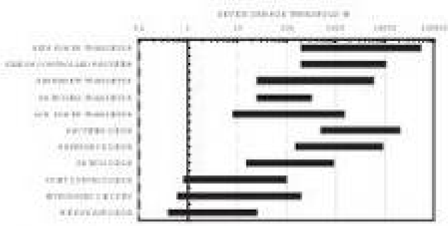

Figure 7. Typical damage threshold levels for 1μs pulses.

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Figure 8. Minor structural battle damage.

4.2 Indirect threats

For this type of threat there is no upset, only damage severity levels. At the lowest level, minor structural damage caused to non-sensitive aircraft parts, for example in Fig. 8, is unlikely to cause mission abortion. However, a missile exploding sufficiently close to the aircraft may cause its destruction. The mechanism is one of impact on the aircraft by missile fragments and the physical destruction of mechanical, hydraulic and electronic systems therein. Missiles are generally designed to detonate close to the aircraft using a proximity fuse and this detonation is targeted where damage is most likely to cause aircraft loss, e.g. engines and the cockpit. When the aircraft gets to this 'end-game', where mission completion dictates avoidance is no longer an option, its vulnerability to damage becomes paramount. A well designed aircraft has adequate defensive aids, such as flares, chaff and RF/EO jamming capabilities to counter the inbound threat and, by careful design of structure and system architectures, an ability to sustain a reasonable amount of damage before mission and aircraft loss occurs.

5.0 RISK AND HAZARD MITIGATION – PREVENTION AND PROTECTION

The reasonably well understood hazards posed to aircraft survivability by direct and indirect EM threats have been described earlier. The risk of being exposed to these hazards, however, is less easy to determine and is a function of many things, not least of which are the aircraft's role and mission, and the scenario in which it has to operate. Roles include fighter, bomber, tanker and transport. Missions include ground attack, counter-air operations, close air support (to the battlefield), strike, interdiction, land reconnaissance, supply and transport, tanker, airborne early warning and control, and maritime patrol. The operational scenario is probably the most complex factor affecting threat exposure risk. The term 'scenario' in this context means a complete mission description, from take-off through battle and return to base. It describes:

- All the own, friendly and enemy's land, sea and air forces, and their locations relative to the aircraft as a function of time.
- Function and performance descriptions of all platforms, weapon systems, survivability features and levels of day/night and all-weather capabilities.
- Geographical factors, season and weather during the mission.

These factors combine to define the operational scenario in terms of probable threat density, aircraft engagement potential and RF, laser and EO EM environment.

5.1 Approach to optimising survivability

Once the above factors are known, risk and hazard mitigation is achieved by adopting an holistic 'prevention and protection' approach, detailed in an earlier paper[7], to assuring maximum survivability levels for a given affordability level. In this approach, survivability components are balanced by an iterative integrated process:

- Evaluate combat effectiveness of aircraft concepts using simulation techniques, taking into account mission-specific weapon system capabilities and other key design factors, e.g. necessary EW capabilities and RCS/IRS to enable to avoidance, evasion or countering of expected threats.
- Conduct trade-offs of key survivability aspects, e.g. signature levels vs cost and operational utility; EW suite complexity vs. cost and delta increase in protection afforded.
- Maximise sustained effectiveness using parametric studies to identify the design features necessary to minimise aircraft loss and maximise mission generation.
- Derive mission and sensor systems' requirements appropriate to the aircraft role, mission and scenarios.

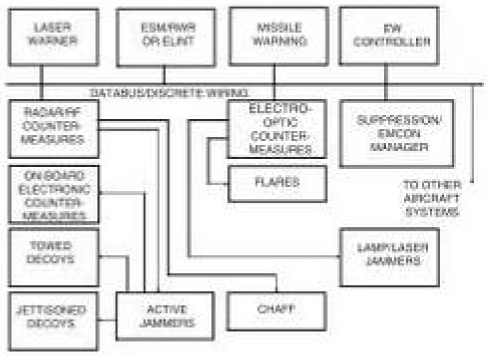

Figure 9. Comprehensive defensive aids system.

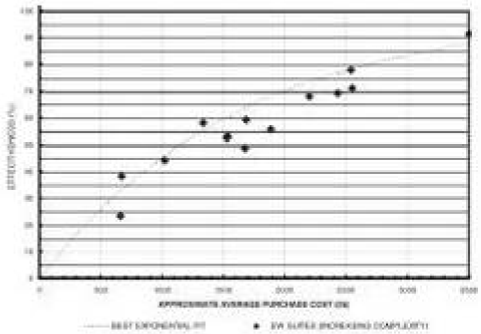

Figure 10. EW suite content *vs* cost *vs* delta increase in effectiveness.

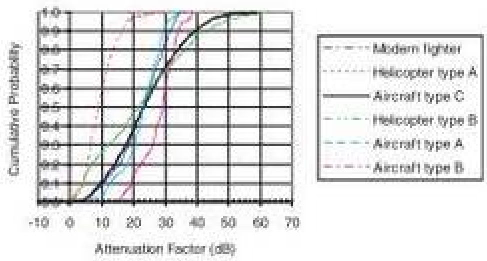

Figure 11. Airframe microwave attenuation statistics.

Figure 12. CEESIM RF threat simulator.

- Minimise aircraft vulnerability per military requirements, e.g. DEF STAN 00-970 Ch.112.
- Conduct survivability analyses to develop battle damage repair requirements in accordance with DEF STAN 00-60 and MIL STD 1388 Task 303.2.11 (survivability trade-offs).

In this 'best practice' approach, the benefits of which are high[8], all survivability components are considered: whole-spectrum, systems-wide EMC; EW capability; RCS/IRS performance and aircraft inherent vulnerability.

5.2 Mitigating the indirect EM threat

Mitigation is achieved through layered philosophies of pre-kill, avoid, evade, counter and sustain. Pre-kill, or destroying the hostile system before it becomes a threat, is by far preferable but difficult to achieve in practice, e.g. SA-6 tactics employed in Bosnia included minimising RF transmission times and high mobility in a 'shoot and scoot' strategy. For pre-kill to be viable, the threat has to be located or detected prior to it engaging the attacking aircraft, or the advantage is lost. Timely intelligence, unfortunately, is difficult to acquire, even with modern unmanned air vehicle (UAV) platforms, although EM/EW UAV variants are likely to contribute much to future conflicts. Avoidance and evasion are useful where re-routing is an option without compromising the mission, or where aircraft with appropriately low RCS and IRS are available. Inevitably, most military aircraft have to go 'in harm's way' to complete the mission. At this point there only remain the Counter and Sustain philosophies. The threat, once the aircraft has been targeted, can often but not always be countered by the aircraft's own DAS and/or through protection by escort aircraft, e.g. suppression of enemy air defence (SEAD) aircraft such as the EA-6B 'Prowler' support jammer. Figure 9 shows the EW components of a comprehensive DAS.

An important consideration is the affordability of threat neutralisation or elimination. DAS cost-effectiveness is difficult to estimate[7], as is SEAD support. Figure 10 highlights this difficulty for the DAS case. It gives the (sanitised) results of earlier BAE Systems single aircraft analyses, with each point representing, from left to right, EW suites with increasing functionality and performance (and hence cost). It confirms the intuitive view that the more capable – and generally the more expensive – the EW suite, the better the chance of survival. It also shows a platform-independent trend that, once a 'modern' level of complexity has been attained, the payback in terms of EW-related increases in threat neutralisation capability markedly reduces with further cost increase.

In the final philosophy, 'sustain', the aircraft's survival, once damaged by missile or shells, is dependent upon its intrinsic vulnerability. In low vulnerability (i.e. high survival probability) designs, various techniques are used to increase mission success probability despite being hit, or at least to guarantee the ability to return to base for repair and return to the fray – rather than outright aircraft loss. Such methods include 'sacrificial' equipment just inside the airframe, protecting important systems such as flying controls; dual redundant systems, located in different places so that one shell (or missile fragment) cannot kill both systems simultaneously; and the separation of fuel and fire-raising agents.

Figure 10 also suggests that, once an existing ('legacy') aircraft of the fighter/bomber type has had the most comprehensive available modern DAS fitted, which can be achieved through a combination of equipment addition, replacement and sequential upgrades, then significant survivability enhancements can probably only be achieved through the following, in indicative priority order:

- Improved on-aircraft sensor integration and data fusion, as discussed inter alia in Ref. 9;
- Use of dedicated SEAD support assets, e.g. EA-6B and Tornado electronic combat and reconnaissance variant;
- Improvements to avoid and evade capability through data-linking situation awareness and targeting information across the land-sea-air electronic battlespace ('network-enabled capability');
- Improvements to the intrinsic physical vunerability of the aircraft; and
- Enhancements targeting lower RCS/IRS and other aircraft signatures.

5.3 Mitigating the direct EM threat

Survivability measure timeliness is also an important factor. Mitigation philosophies are as above by title but with subtly different emphasis and implementation. Generally, engagements by SAM, AAM and AAA have a finite duration, usually from a few seconds to a few minutes. Conversely, direct EM threats tend to be instantaneous, e.g. RF and laser DEW, hence their other name 'speed of light weapons'. While it could be argued that DEW

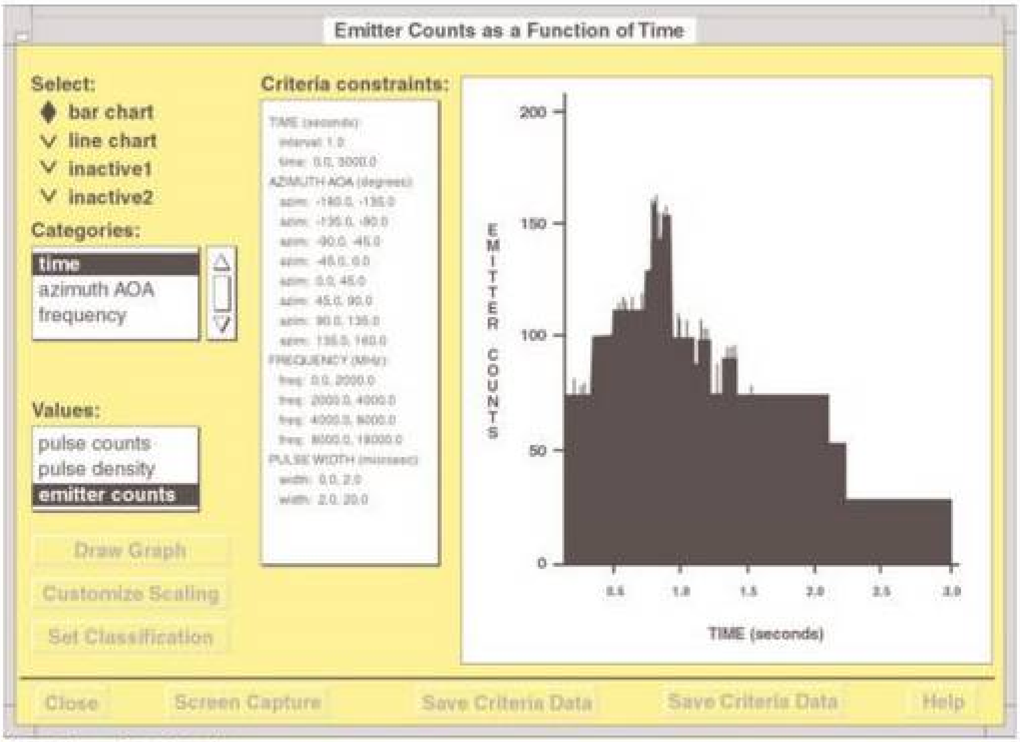

Figure 13. Example EGA output.

could be Pre-Killed, lightning strike could not. It is impossible to avoid or evade the general RF/EO environment – aircraft design must cater for this reality. Countering these threats is also not viable. Therefore, the emphasis is greatly focused on the 'sustain' philosophy. Low vulnerability to these threats can be achieved by implementing:

- Stringent EMC/EMI control, specification, design and installation practices. The resilience of avionic and electrical systems to field strengths to be encountered is primarily dependent upon the shielding offered by the airframe and the intrinsic EM resilience of the avionic/electrical system or box itself. While it is possible to modify the EMC characteristics of an individual avionics box post-manufacture, it is difficult to say the same for the airframe. In both cases retro-modification to achieve higher resilience is technically complex, expensive and very time consuming.

  Much effort has thus been expended over the last decade on attaining computer modelling capabilities to enable whole-aircraft and system EM performance prediction, and to ensure adequate safety margins are built in to the aircraft at the outset. This has been enabled by the major computing power increases seen over the same time frame, but even now whole-aircraft detail EM modelling is not yet possible at the higher GHz frequencies of interest to the EW community. As a result the accurate prediction by modelling of full-spectrum EMC, installed antenna and RF systems interoperability performance still remains an elusive goal, with predictions usually based on a combination of modelled and measured data. For example, Fig. 11 from Ref. 10 shows such a prediction of airframe shielding, in the microwave band, based on statistical analysis of measurements taken on a number of military fixed and rotary wing aircraft.
- RF/EO/optical sensor and lightning strike protection schemes, noting that aircraft must withstand lightning strike attachment and therefore have little concern about nearby strikes.
- Sensor fusion and redundancy to optimise situation knowledge and awareness, whilst reducing decision making reliance on any single sensor.

6.0 CHALLENGING ISSUES AND INNOVATIVE SOLUTIONS

Assuring military aircraft survival is a complex, multi-disciplinary systems engineering problem and obstacles exist which prevent 'zero attrition' guarantees. Some are outlined below, in no particular order, with an indication of how these are being resolved through industry development of innovative solutions. It is reasonable to say that the risk and hazard of most are being mitigated by the increasing and complementary use of powerful modelling tools and techniques to assist in the prediction, specification and verification of EM and EW performance. Despite these continuing advances, some goals are thought likely to remain elusive for the foreseeable future.

Figure 14. BAE Systems' EW test facility.

Figure 15. IR signature measurement and analysis system.

6.1 Precise EM environment definition

It is curren tly impossible to construct a precise EM environment definition for realistic operational scenarios. For example, in the RF case, there will be energy from hundreds of RF emitters impinging on an aircraft in wartime flight. The combination of aircraft manoeuvre, multiple scanning RF emitters, weather and terrain effects; near-field effects, installed antenna performance and inter-/intra-aircraft multi-path/scattering means that predicting power density *vs* frequency at the aircraft with any confidence is difficult.

Although challenging, high fidelity RF environment prediction is possible using widely available real-time RF threat simulators, see Fig. 12, and associated scenario modelling and analysis tools[11]. The simulators, which are primarily required for the Test and Evaluation (T&E) of modern EW suites[12] do, however, carry a £multi-M price tag.

Attaining a better than present definition of operational RF environments is likely to be required to enable adequate specification of the upcoming generation of 'digital' EW receivers, whose potential includes a number of operationally useful performance benefits, of which the most notable are:

- better threat recognition capability and decreased emitter ambiguity (leading to false alarms), and
- improved threat direction finding accuracy and geo-location capability.

A good example of an environment modelling and analysis tool is the environment generation and analysis (EGA) software package, which is used for the creation and analysis of static and dynamic, complex, multi-emitter RF signal environments. It is actually a replication of the front-end of a full-up simulator, with the capability to port resultant emitter scenarios directly into the simulators for post-antenna direct injection into EW receiver systems or for free space irradiation of EW systems installed on aircraft. Figure 13 is an example output of the EGA tool.

These simulators and tools like EGA are used for EW operational and system requirements analysis, systems design and development, signal processing algorithm testing and sub-system/system/platform T&E. At this time most cover the RF domain, but IR and UV simulation and stimulation systems are becoming more common as the world-wide move towards fused RF/EO sensor information gathers pace. Potential also exists for RF simulator/EGA use in the EMC arena, should a better EM environment definition be required than those in standards such as MIL-STD-461/462.

6.2 Precise specifications

It is difficult to capture a fully comprehensive view of the 'real world' use of a product and an exact definition of what constitutes 'fully fit for purpose' from the customer's and end-user's perspectives. This is especially so for military aircraft. Despite this, major moves towards the precise specification goal have been made in recent years. This is most visible at the avionic equipment specification level where, for example on EW systems, modern specifications are much enhanced in quality and range of detail. They now include better definitions of all aspects of equipment function and performance, especially in EM-related areas, and how performance is to be contractually verified. The importance to survivability of high quality specifications at the equipment, sub-system, systems and platform levels cannot be over-emphasised.

6.3 Invincible aircraft

No aircraft is invincible. A realisable and affordable goal for aircraft robustness against EM threats is the inclusion of a sensible level of designed-in protection against each threat sub-type, augmented by an aircraft and systems design which enables – at minimum – safe return to base for repair, if and when damaged by those threats. Such protection schemes include EM shielding/filtering, RF receiver input overload protection, frequency selective surfaces and optical aperture shutters. The optimum survivability situation is attained when all threats can be accurately defined whilst the aircraft is still 'on the drawing board'. Unfortunately, this never happens in practice as new threats emerge during the aircraft's development and operating life. However, even for in-service aircraft, the situation can be improved by retrofit application of survivability enhancement measures. It should be noted that this is easier for protection against the indirect EM threat, where more and/or better EW equipment can usually be fitted and tactics refined, than for the direct threat, where the airframe, wiring and avionics' EM susceptibility would need to be altered.

6.4 EM and EW performance verification

EM and EW performance verification is generally difficult, time-consuming and requires expensive T&E facilities. Aircraft manufacturers are usually contracted to provide evidence that the aircraft and its systems meet their design specifications. This is achieved through a combination of inspections, analyses, tests and demonstrations. These

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Figure 16. Lightning strike testing in EWTF anechoic chamber.

are conducted at equipment suppliers' facilities, in avionic integration and other laboratories at the aircraft manufacturer's premises, on aircraft ground-based trials and via flight trials on test ranges. For example, BAE Systems' EW Test Facility (EWTF) in the North West of England, see Fig. 14, is used for whole aircraft EW and EMH testing, and for EW systems and sub-systems T&E[13]. The EWTF contains key capabilities for RF stimulation, jammer/other RF signal evaluation, EW environment modelling and analysis (including an EGA tool), as well as high power RF amplifiers and a full-threat lighting strike test generator.

6.5 Countermeasure effectiveness issues

Prediction and evaluation of countermeasure effectiveness against threats is difficult in the extreme[14]. There are, as described earlier, many factors affecting the missile-aircraft-countermeasure altercation, many which apply in combination and some which are not predictable with any level of confidence. Countermeasure effectiveness is thus almost impossible to guarantee. It is a complex combination of installed EW system technical performance, which includes intelligence-based threat data and countermeasure techniques with which it is programmed, and tactics used by aircrew. Technical performance is under the aircraft prime contractor's control and is defined in technical specifications, and is measurable and verifiable. Techniques ('pre-flight messages') and tactics, on the other hand, are under the User's control, are constrained by those specifications and are derived from analysis, experience and trials. Countermeasure effectiveness is thus maximised by the refinement of techniques and tactics, both of which are informed by experience and optimised by trials. As the metrics and measurement of effectiveness are open to debate and interpretation, it is difficult to contract 'effectiveness' levels for countermeasures and counter-countermeasures.

For example, an EW system's ability to detect RF-guided threats and apply appropriate and timely countermeasures is usually contracted with the aircraft supplier. However, the aircrew tactics, e.g. manoeuvre and particular methods of EW systems operation, are highly specific to the threat in question and rely on an intimate knowledge of that threat and its susceptibilities. Such knowledge is hard to obtain, even if one has an actual threat to evaluate. It is usually 'perishable', as the countermeasure is only valid as long as the opposition doesn't know you know that susceptibility – thereafter the weapon system is likely to be quickly modified to remove the susceptibility and the countermeasure no longer works. Such information is thus accorded the highest level of security and not normally released by the military to industry.

6.6 Prediction and assurance of adequately low aircraft RCS/IRS levels

These remain technically difficult and nationally sensitive issues. Ref. 15 covers interesting aspects of RCS and counter-stealth radar. As a generalisation it is fair to say that militarily useful stealth performance has to be designed in at the outset. Retrofitting this capability to existing platforms is generally difficult, costly and of questionable value[16], although it can offer positive benefits through reduced jammer power requirement or in improved jamming effectiveness via enhanced jam-to-signal ratio. EM modelling and airframe integration design forms a vital part of the signatures design and assurance process, and ongoing computing power advances have been helpful in mitigating risks. IRS prediction is arguably less mature, and thus greater reliance is currently placed on the use of measured IRS data from in-flight aircraft. Modern measurement and analysis methods, such as those of BAE Systems' Mobile IR ground-to-air tracker (MIRGAT) system, see Fig. 15, offer significant benefits to the above process.

6.7 Whole aircraft EMC testing

Generating high power EM fields in free space, to verify specified whole aircraft EMC, with sufficient safety margins, is highly expensive and can cause EM spectrum pollution. Such trials are logistically complex, time-consuming and have poor repeatability. A number of facilities have such capabilities, but none totally covers the full frequency range required with high enough field strengths to enable specified performance to be wholly verified by test. The use of free field simulation techniques in the EMC design and evaluation processes has been seen to mitigate this issue to a level agreeable to aircraft customers. Established simulation techniques include low level swept frequency, loom bulk current injection and airframe direct current injection. In parallel with the development of these techniques, computational EM techniques are creating reduced reliance on aircraft testing.

6.8 Lightning strike testing

Whilst the value of full- and sub-threat lightning strike testing on part structures (e.g. wings) and sub-scale models is recognised as an important aircraft design and development process element, it cannot replace the need for performance verification by whole aircraft testing. Figure 16 shows the Typhoon (previously named 'Eurofighter') undergoing such tests in the EWTF. Increases in computing power offer the opportunity for the modelling of whole aircraft lighting strike. This is, however, unlikely to entirely remove the need for at least sub-threat whole aircraft testing, if only on the 'first of type' aircraft for the purpose of validating models, prior to use for clearing other individual aircraft of that type.

7.0 CONCLUSION

Control or dominance of the EM environment is essential to assuring combat success and flight safety. The past 25 years have seen significant enhancements in the understanding of electromagnetics as applied to complete aircraft behaviour in general and, in particular, the capability to adequately specify and verify performance in the technologically complex areas of EMC/EMH, EW, Signatures and Vulnerability – all key components of Survivability.

For the future, military aircraft and system-of-systems providers will have to cater for mastery of an ever-changing and increasingly complex EM-related environment that is likely to include:

- Newer SAM, AAM and AAA types, in addition to established and elderly designs in service world-wide. These weapon systems are likely to have, or be modified to have, multi-spectral guidance systems, making them harder to counter.
- Threats with lower power emissions and far shorter transmit times than at present. In combination with other low probability of intercept techniques, threat detection will become increasingly difficult using current techniques. Examples of this have been witnessed in recent conflicts, where even the humble mobile telephone has found a place in the opposition's IADS.
- An increased probability of encountering RF and Laser DEW.
- An increasingly complex communications environment, required to enable true co-operative sensing and network enabled capability.

The trend is towards force protection where both the sensors and ECM capability of individual aircraft operating as part of a force are co-ordinated by networking the aircraft EW systems, affording a much greater effective capability and hence improved survivability than an individual self protect system.

A need thus remains for improved military aircraft designs and implementations, to ensure desired survivability performance. Such improvements will lead to optimised mission success potential and better aircrew life expectancy.

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Electronics Systems and Software

KEEPING MILITARY AIRCRAFT SAFE FROM ELECTROMAGNETIC DANGERS

SPECIAL REPORT: CUTTING THE COST OF VERIFICATION

SYSTEM DESIGN: TRANSACTIONS SPEED SIMULATIONS

OUT OF CONTROL? CHIP COSTS HIT THE PAIN BARRIER

MILITARY AIRCRAFT COMBAT THE ELECTROMAGNETIC ENVIRONMENT

ELECTROMAGNETIC COMPATIBILITY TAKES ON A LIFE OR DEATH IMPORTANCE IN MILITARY AIRCRAFT AS MULTI-SENSOR MISSILE SYSTEMS, ENERGY WEAPONS AND THE NATURAL ELECTROMAGNETIC ENVIRONMENT POSE SERIOUS HAZARDS TO SURVIVAL.

by Mike Pywell

From the perspective of the military aircraft and avionic systems designer, the electromagnetic (EM) environment can be an enabler, through the use of navigation aids, radar and radio communications. But the EM environment is also a potential disabler, as threats from weapons based on EM technologies and the environment itself can harm or destroy the aircraft. There are two distinct types of EM-based threats that concern military aircraft designers and pilots alike. The first is the direct-threat category, which includes lightning strikes, EM pulses produced by nuclear weapons and directed-energy weapons. The second, the indirect threat category, includes weapons such as radar- and infrared-guided surface-to-air and air-to-air missiles.

Lightning causes problems in two ways. A strike landing on an aircraft in flight can cause physical damage at the entry and exit points and high currents to flow on and within the airframe, which can cause damage to mechanical and electronic components. A nearby lightning strike can cause high EM fields to

TABLE 1: RF INTERFERENCE AND ITS DOCUMENTED EFFECTS

AIRCRAFT	SOURCE	CAUSE/ EFFECT
USS Forrestal: Aircraft carrier	Carrier radar	Poorly shielded plug: Missile fired into other aircraft: 134 dead; $72m damage
Black Hawk helicopter	Radar/ radio masts	Several crashes attributed to RF interference affecting flight control systems
Various passenger aircraft	Portable devices	24 pilot reports of RF interference due to passenger-operated electronic devices
Boeing 747-100	Camcorder	Slow left turn
Boeing 747-200	Two laptop computers	Compass moved 150 degrees
Augusta 109 helicopter	Radio mast	Spurious engine readings, to normal after 7-10 seconds
Various	Radio masts	Spurious readings on GPS

be propagated at the aircraft, as if the strike itself were a RF transmitter, which can upset or damage electronic systems. EM pulses, whether produced by nuclear or non-nuclear means, have different waveforms to lightning strikes but can also upset electronics. It is generally accepted that transmitting arrangements with high enough field strengths for use as directed-energy weapons exist, albeit some only yet in the laboratory with operational questions persisting for others. Systems capable of generating and projecting appropriately high levels of RF energy at militarily useful ranges remain elusive for a number of significant technological reasons, but there is a potential threat in the future.

The other main category of EM threat, the indirect threat, includes weapons such as radar-guided surface-to-air missiles. Indirect threats pose the most serious and prolific hazard to aircraft. They can be guided by radar, radio or electro-optical measurements or signals. Multi-spectral or 'dual-mode' guidance has become a recent trend, to ensure the missile can be effective even when being jammed in one EM sub-band by the target aircraft's self-protection system. Despite this trend, single-mode RF or electro-optical guidance systems predominate in the case of surface-to-air missiles. The situation is more complex for anti-aircraft artillery systems as it is difficult to isolate the precise guidance methods for all the approximately 31 types and 43,000 systems in use. Many are single-sensor systems on delivery, but often later augmented with other sensors.

THREAT LETHALITY

Many factors affect the success of threat systems when engaging aircraft. For example, flying high degrades the surface threat's targeting accuracy and can prevent the anti-aircraft artillery and man-portable missile systems from engaging at all. Flying high, however, exposes the aircraft to an increased threat from RF-guided surface-to-air missiles. Further, stealthy designs can maximise delay before the threat detects the aircraft, which limits the threat's targeting time and reduces the probability of a weapon firing and hitting.

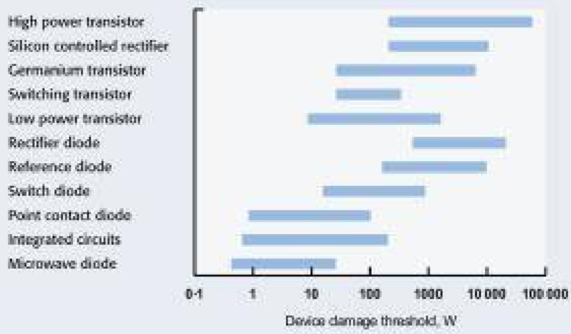
To put the missile threat into perspective, Table 2 gives open-source kill data from a number of conflicts. Although simplistic in nature, the table demonstrates that the public's perception that missiles are 'fire-one-

TABLE 2: KILL DATA FOR VARIOUS MISSILE TYPES

Threat	Type	Code-name	Conflict/ Era	Combat firings	Kills	%Kill rate
Infrared-surface-to-air missile	SA-7a	Grail	Vietnam war (1965-75)	[not available]	[not available]	33
Infrared-surface-to-air missile	SA-7b	Grail	Yom Kippur (1973)	4356	6	0.14
RF-surface-to-air missile	SA-2	Guideline	Vietnam war	9058	150	1.65
RF-surface-to-air missile	SA-6	Gainful	Yom Kippur war	840	20	2.3
Infrared air-to-air missile	All AIM-9	Sidewinder	up to January 1990	1382	308	22.3
RF air-to-air missile	AIM-7	Sparrow	1958-1994	654	96	14.7*

* Wide variation by conflict: Vietnam 8%, Yom Kippur 33%, Bekaa Valley (1973) 50%, Libya (1982-9) 33% and Gulf War (1991) 62%.

FIG. 1 DAMAGE POWER LEVELS OF ELECTRONIC COMPONENTS.



kill-one, fire-another-kill-another' weapons is not true. The reality is that each and every engagement is a highly probabilistic event with an outcome that is rarely predictable. Table 2 also suggests that infrared-guided surface-to-air missiles apparently pose the most significant threat to aircraft. Although true in absolute terms, this masks the real situation. RF-guided threats are generally being adequately countered by the tactics and RF electronic countermeasures, or jammers, used on modern aircraft.

Indirect threats generally pose a much higher risk during conflicts than direct threats, even though the latter can also cause mission failure or aircraft loss. But it is unacceptable for aircraft to be brought down by a lightning strike onto a populated area during war or peacetime. So, the direct and indirect threats are treated with equal seriousness by aircraft designers and avionics engineers.

In the case of direct threats, it is important to discriminate between upsets and damage. The former normally does not significantly affect survivability but may compromise the success of a mission. The latter will certainly adversely affect both. With few exceptions, an upset is a temporary and recoverable situation on once the interference is removed. There are a number of published examples of the susceptibility of electronic circuitry to high-power RF fields. Table 1 gives a few examples of upsets and the consequent knock-on effects. It is important to recognise that there is usually a significant power density differential between upset and component damage caused directly by a powerful EM field. A typical figure is 100 times higher for damage than upset, although the actual figure varies widely and depends heavily on the specific threat type and electronic device concerned. Figure 1, from the Taylor and Younan paper "Effects from HPM Illumination", shows the damage threshold ranges of some types of electronic component.

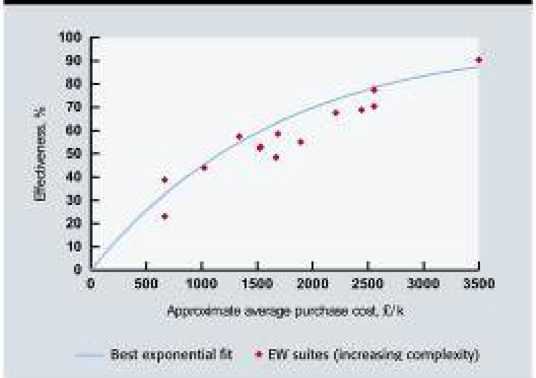
DETERMINING SURVIVABILITY

The risk of being exposed to various threats is not easy to determine and is a function of many things, not least of which are the aircraft's role, mission and scenario in which it has to operate. The term 'scenario' in this context means a complete mission description, from take-off through battle and return to base. Once these factors are known, risk and hazard mitigation is achieved by adopting an holistic 'prevention and protection' approach to assuring maximum survivability levels for a given affordability level. In this approach, survivability components are balanced by an iterative integrated process, using a combination of simulation, parametric studies and survivability analyses. In this approach, all survivability components are considered: whole-spectrum, systems-wide EM compatibility; electronic warfare capability; stealth performance; and aircraft inherent vulnerability.

Mitigation is achieved through a combination of possible techniques: pre-kill; avoidance; evasion; counter; and sustain. Pre-kill, or destroying the hostile system before it becomes a threat, is by far preferable but difficult to achieve in practice. For pre-kill to be viable, the threat has to be located or detected prior to it engaging the attacking aircraft, or the advantage is lost. Timely intelligence, unfortunately, is difficult to acquire, even with modern unmanned air vehicles. Avoidance and evasion are useful where re-routing is an option without compromising the mission, or where sufficiently stealthy aircraft are available. Inevitably, most military aircraft have to go in harm's way to complete the mission. At this point there only remain the approaches of counter and sustain. The threat, once the aircraft has been targeted, can often be countered by the aircraft's own electronic warfare (EW) systems, or by escort aircraft such as the EA-6B Prowler support jammer.

An important consideration is the affordability

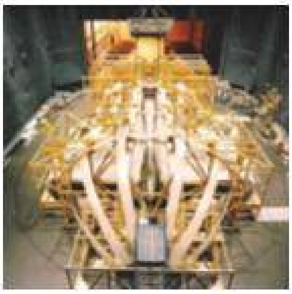
FIG. 2 EFFECTIVENESS AGAINST INCREASING COST OF ELECTRONIC WARFARE SYSTEMS.



of threat neutralisation or elimination. Cost-effectiveness is difficult to estimate. Figure 2 highlights this difficulty. It gives the sanitised results of earlier BAE Systems analyses, with each point representing, from left to right, suites with increasing functionality and performance, and cost. It confirms the intuitive view that the more capable – and generally the more expensive – the suite, the better the chance of survival. It also shows a platform-independent trend that, once a 'modern' level of complexity has been attained, the payback in terms of EW-related increases in threat neutralisation capability markedly reduces with further cost increases.

The sustain technique depends on the use of various design philosophies to maintain operation despite being hit, or at least to guarantee the ability to return to base for repair. Such techniques include: 'sacrificial' equipment just inside the airframe, protecting important systems such as flying controls; dual redundant systems, located in different places so that one shell cannot kill both systems simultaneously; and the separation of fuel and fire-raising agents.

Fig. 3 Typhoon in lightning-strike tests



Survivability measure timeliness is also an important factor. Missile engagements and other indirect threats have a finite duration, usually from a few seconds to a few minutes. Conversely, direct EM threats tend to be instantaneous. Although directed-energy weapons could (with great difficulty) be pre-killed, lightning strikes cannot. Therefore, the emphasis for both is greatly focused on the sustain technique. Low vulnerability to these threats can be achieved by implementing: stringent EM compatibility design and installation practices; sensor protection schemes; and sensor fusion and redundancy to reduce reliance on any single sensor.

OPTIMISING SURVIVABILITY

It is currently impossible to construct a precise EM environment definition for realistic operational scenarios. For example, just in the RF case, there will be energy from hundreds of RF emitters impinging on an aircraft in wartime flight. Real-time RF threat simulators are available, albeit with a multi-million pound price tag. These simulators are used for electronic warfare operational analysis, systems design and development, and test and evaluation. At this time most cover the RF domain, but infrared and ultraviolet simulation and stimulation systems are becoming more common as the world-wide move towards fused sensor systems gathers pace. Potential also exists for RF threat simulator use in the EM compatibility arena, should a better EM environment definition be required than those used in standards such as MIL-STD-461/462.

Despite the problems of building a precise environment definition, major moves towards the goal of obtaining precise specifications have been made in recent years. This is most visible at the avionic equipment specification level. The specifications now include better definitions of all aspects of equipment function and performance, especially in EM-related areas, and how performance is to be contractually verified. The optimum survivability situation is attained when all threats can be accurately defined while the aircraft is still on the drawing board. Unfortunately, this never happens in practice as new and enhanced threats emerge during the aircraft's operating life. However, even for in-service aircraft, the situation can be improved by retrofitting survivability enhancement measures. It should be noted that this is easier for protection against the indirect EM threat, where more or better electronic warfare equipment can be fitted and tactics refined, than for the direct threat, where the airframe, wiring and avionics' EM susceptibility would need to be altered.

WHOLE AIRCRAFT TESTING

EM and electronic warfare performance verification is generally difficult, time-consuming and requires expensive test and evaluation facilities. Aircraft

EA6 Prowler aircraft

manufacturers are usually contracted to provide evidence that the aircraft and its systems meet their design specifications. This is achieved through a combination of inspections, analyses, tests and demonstrations. These are conducted at equipment suppliers' facilities, in avionic integration and other laboratories at the aircraft manufacturer's premises, on aircraft ground-based trials and through flight trials on test ranges. For example, BAE Systems' Electronic Warfare Test Facility (EWTF) in the North West of England is used for whole aircraft electronic warfare and lightning strike testing.

Full- and sub-threat lightning strike testing on part structures, such as wings, and sub-scale models, is recognised as an important aircraft design and development process element. But it cannot replace the need for performance verification by whole aircraft testing. Figure 3 shows the Typhoon undergoing such tests in the EWTF. Increases in computing power offer the opportunity for the modelling of whole aircraft lighting strikes. This is, however, unlikely to remove the need for whole aircraft testing, if only on the first-of-type aircraft for the purpose of validating the model, prior to its use for clearing other individual aircraft of that type.

Generating high power EM fields in free space, to verify specified whole aircraft EM compatibility, with sufficient safety margins, is highly expensive and can cause EM spectrum pollution. Such trials are logistically complex, time-consuming and have poor repeatability. A number of facilities have such capabilities, but none totally covers the full frequency range required with high enough field strengths to enable specified performance to be wholly verified by test. The use of free-field simulation techniques in EM compatibility design and evaluation processes, such as low-level swept frequency, bulk-current injection and direct-current injection, has been seen to mitigate this issue to a level agreeable to aircraft customers. Computational EM techniques offer some promise for future reduced reliance on aircraft testing.

CONCLUSIONS

Control or dominance of the EM environment is essential to assuring combat success. The last 25 years have seen significant enhancements in the understanding of EM compatibility as applied to complete aircraft behaviour in general and, in particular, the capability to adequately specify and verify performance in the technologically complex areas of electronic warfare, stealth and vulnerability. For the future, military aircraft and systems providers will have to cater for an ever-changing and increasingly complex EM-related threat environment that is likely to include new and established, multi-sensor missile-guidance systems, and threats with lower power emissions and far shorter transmit times than at present. Threat detection will become increasingly difficult using current techniques. Examples of this have been witnessed in recent conflicts, where even the humble mobile telephone has found a place in the opposition's armoury.

This article appears to paint a pessimistic picture for military aircrew life expectancy. This is not necessarily the case, since everything in life is a question of risk and hazard balancing. With the application of the risk and hazard mitigators described above, it is possible to offer affordable aircraft with superior survivability.

Mike Pywell is electronic warfare technology programme manager and electronic warfare systems specialist at BAE Systems.

Survivability – A Reward for Integrated Thinking

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ABSTRACT

The key to survival is reliant on accepting that Survivability has three major elements, namely: damage avoidance, damage tolerance and damage repair. The Survivability of a platform must consider, in a balanced manner, all three of these elements to effectively reduce attrition and achieve the required wartime performance.

Damage avoidance is a result of the performance characteristics and mission planning for the weapon system. Although, increasingly the new concepts of network enabled warfare have a significant impact on damage avoidance. In the case of an aircraft the characteristics of interest include observability, defensive aids installed performance and manoeuvrability. The mission planning must consider the concept of operation and tactics within the capabilities of the aircraft.

Design for damage tolerance must include the following considerations:

- *The vulnerability of the complete aircraft to potentially, fatal damage which could result in loss of the aircraft.*
- *Significant damage resulting in a loss of performance (possibly causing mission failure and significant out-of-service time for repair).*
- *Slight damage resulting in a rapid repair not impacting on availability.*

Both systems and structure are of concern and the modern tendency for criticality of the design and close integration of each requires very careful consideration of the impact of threats.

Damage repair has more recently become a vital part of the support of the aircraft. Rapid but effective repairs are essential to maintain valuable combat assets in theatre.

New airframe materials (e.g. composites) and systems technologies (e.g. wide-band data-buses) whilst offering huge performance improvements must not impact in a negative way on the ability to repair the aircraft.

It can be seen that a holistic approach is essential to Survivability in order to optimise the technological investment and so achieve the Survivability goal. This is made considerably more challenging by the very wide range of technical disciplines that must contribute to the end goal.

Modelling tools, test facilities, organisational design and integrated product development techniques all have an important role to play. However it is vital that all projects must have an appropriately expressed Survivability requirement and an agreed verification and qualification philosophy for each stage of the development of the project. Such a focus is essential in order that a requirement can be met despite the fact that the overall Survivability performance can not be fully validated – until the first days of combat use of the aircraft.

Paper presented at the RTO AVT Symposium AVT-087/RSY-012 on "Combat Survivability of Air, Sea and Land Vehicles", held in Aalborg, Denmark, 23-26 September 2002, and published in RTO-MP-090.

1.0 INTRODUCTION

As discussed in the abstract, the key to survival is reliant on accepting that Survivability has three elements, namely: damage avoidance, damage tolerance and damage repair. The Survivability of a weapon system must consider, in a balanced manner, all three of these elements to effectively reduce attrition and achieve the required wartime performance (see Ref.1).

A number of changes in procurement policy in the UK have had a dramatic effect on the way in which we consider these issues in the defence industry. The most significant changes include:

- reduction in the extent of Government Furnished Equipment (GFE) on which Survivability relies in part (e.g. EW systems).
- much greater consideration of the through-life costs of a weapon system.
- understandable, constant downward pressure on weapon system purchase costs, often against fixed or firm priced contracts.

This paper considers some of the changes which need to be made in order to ensure that these changes can be addressed whilst still ensuring a competitive weapon system can be fielded in both the financial and war fighting sense.

In order of desirability and chronology of tactics the paper will address the impact of the changes on damage avoidance, tolerance and repair and then considers how a holistic view of all three could result in a complete weapon system being optimised for Survivability. Finally the considerations are extended to cover the new circumstances of network centric warfare.

2.0 DAMAGE AVOIDANCE

Fig. 1 shows the major components or considerations upon which the ability to avoid damage rests. Until recently some of the major components of this mix of air platform properties were GFE the most significant example being the EW system. This is not presently the case. However, later in the paper we shall briefly cover the growing influence on damage avoidance of the capabilities of a network-enabled battle-space. To the platform prime contractor or supplier this capability will essentially GFE.

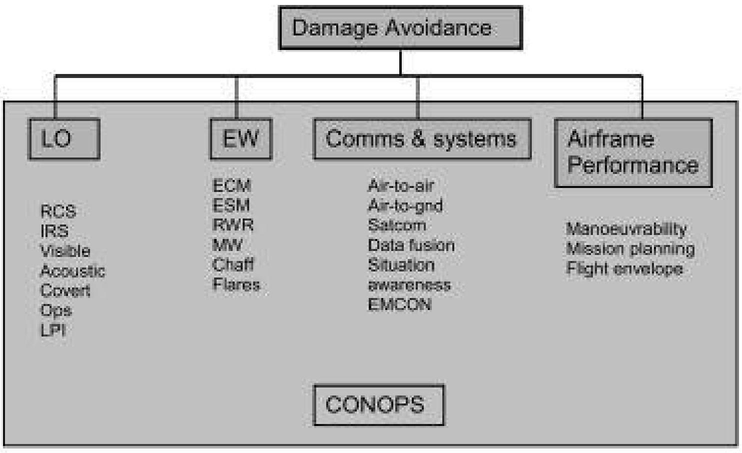

Figure 1: The Major Properties Influencing Survivability.

For the purposes of this section of the paper a platform supplier's viewpoint is taken, assuming a sufficient and robust network is in place.

In order to contain the risk against a fixed price contract of integrating an advanced EW system with a military aircraft, BAE Systems has designed and built an Electronic Warfare Test Facility (EWTF) at the Warton site. This facility enables equipment, sub-systems and ultimately complete aircraft to be tested in a secure, controlled environment. The capability allows much more efficient use of flight trial times and provides better quality results towards demonstrating compliance with the customer-stated aircraft requirement.

Similar approaches have been adopted in other areas, although, cognisance has been taken of the existence or otherwise of suitable facilities outside the company.

Placing these responsibilities within the defence industry has strengthened its capabilities and clarified the costs associated with any particular property of the air platform. It will be shown later that this clarification of costs is important in the balance of investment decisions necessary across the Survivability problem space.

In order to move the responsibility for a particular aspect into industry the customer must express his requirements as a meaningful and demonstrable specification. At present the requirements are expressed as individual performance targets (e.g. RCS, EW system performance etc). This does not allow industry to trade across the problem space of "damage avoidance". Furthermore the requirements are often expressed in deterministic terms, whereas the properties being specified have more meaning as stochastic requirements. We shall see later that developments in the creation and casting of requirements are needed.

3.0 DAMAGE TOLERANCE

Fig. 2 shows the major concerns for damage tolerance. There is a grouping of man-made, intentional, hostile threats, against which the aircraft must have battle damage tolerance. There is also a connected set of peace-time, potentially damaging threats (e.g. Lightning strike) which are connected and although they are beyond the scope of this paper, they have to be considered in the design.

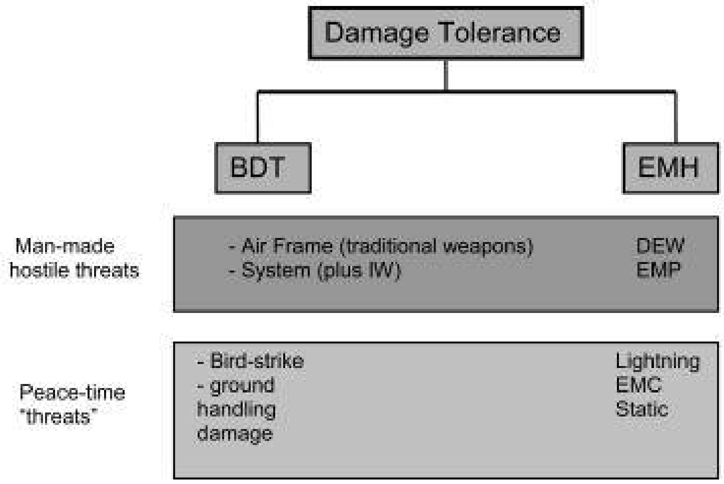

Figure 2: The Major Considerations Influencing Damage Tolerance.

In the past the quality of the design with respect to damage tolerance or electromagnetic resilience was based on following "good practice" as outlined in Defence or Military Standards (e.g. UK DEF STAN 00-970 or Mil Std 461). These were written based on observations from past conflicts in the case of damage tolerance. In the case of the latent behaviour of systems, for example EMC, these were often based on equipment centred viewpoints, but nevertheless generally contained good advice. In an environment of fixed price contracting and a more "arms length" arrangement, there is always pressure on design teams to save costs and without the ultimate qualification to think about, vital integrated design issues can be driven out.

Understandably, procurement contracts have rapidly moved towards performance based specifications with associated routes to qualification, often involving a suitable mix of component and whole platform testing resulting in qualification.

There are a number of challenges in these changes, namely:

- Whole platform testing is at best limited in its ability to verify performance against the specification or at worst totally impractical.
- The facilities required to carry out much of the platform level testing are expensive and often under-utilised, particularly with the longer time-spans between major projects.
- The loss of automatic Government funding of such facilities has resulted in loss of some of these facilities.
- Much of the utilisation of these facilities in the past was exploratory testing from which "good practice" was passed on in Defence Standards to guide the design of platforms of the day. Loss of such facilities and/or the funding prevents the updating of such guidance for platforms using later technology.

Industry's necessary response to this has been to invest in:

- The development of more sophisticated modelling techniques, validated by small-scale experiments.
- Greater investment in establishing the "good practice" associated with new technologies employed in recent platforms.
- The investment in whole aircraft test facilities where a real business case exists.

Within BAE Systems, Air Systems, these investments have been made, particularly in the field of Electromagnetics. A whole aircraft testing capability has been developed for some time-domain threats and some frequency bands, thus giving a basic verification test result for the whole aircraft. This is combined with analysis involving multi-tier verification evidence (e.g. equipment and sub-system test results) and a portfolio of design control including design deviations, contributes to the demonstration of meeting the air platform specification.

Fig. 3 shows the generic approach to qualification adopted in electromagnetic performance issues, including Nuclear Electromagnetic Pulse. In the field of Battle Damage tolerance, whole aircraft testing is impractical, expensive and not particularly informative for the amount of testing which could be generally afforded. In this case, the approach of Fig. 3 is reduced to that of Fig. 4.

In both cases it can be seen that the philosophy of the design must address the issues from the earliest conceptual design using relatively crude modelling and engineering judgement in order to arrive at a suitable configuration to satisfy the requirements.

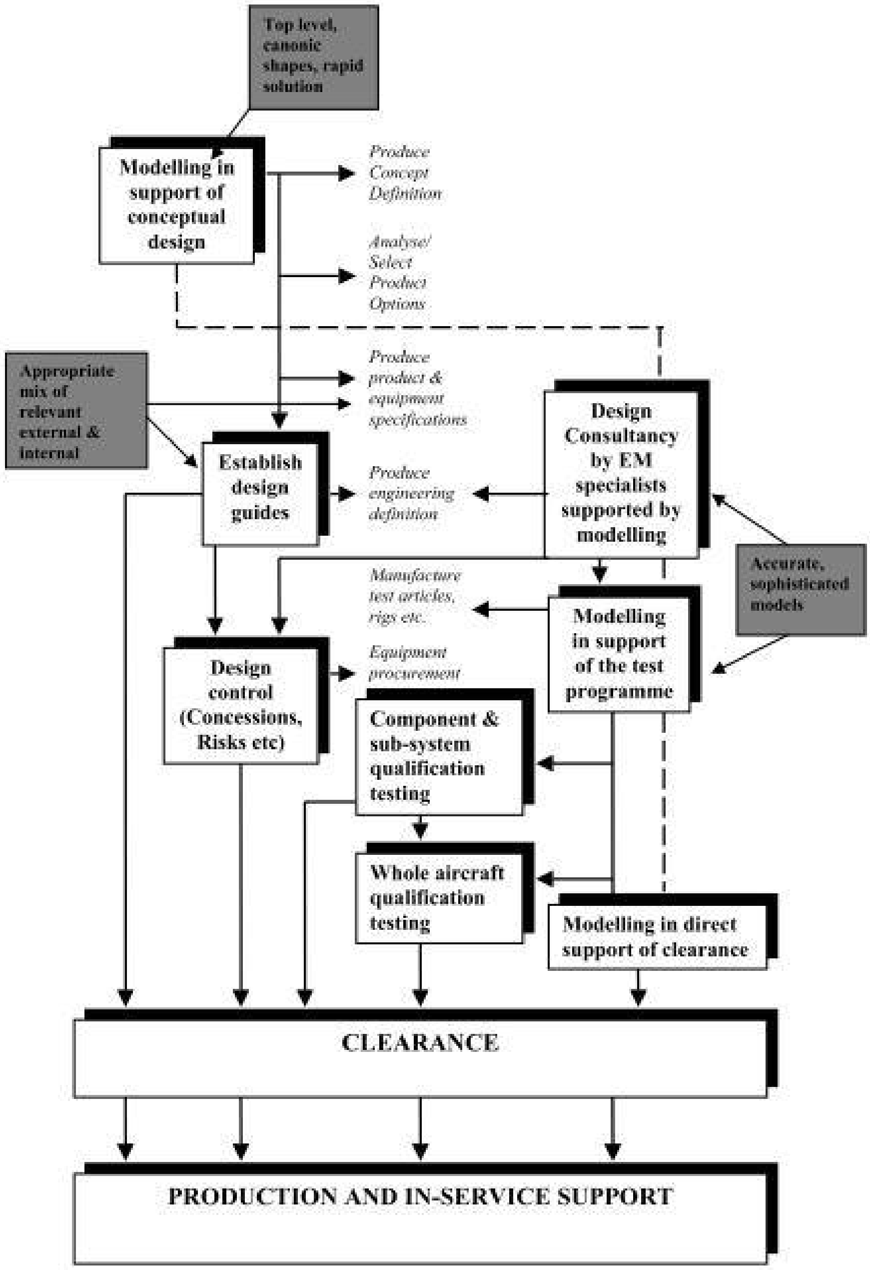

Figure 3: The Generic Design and Qualification Process for Electromagnetics.

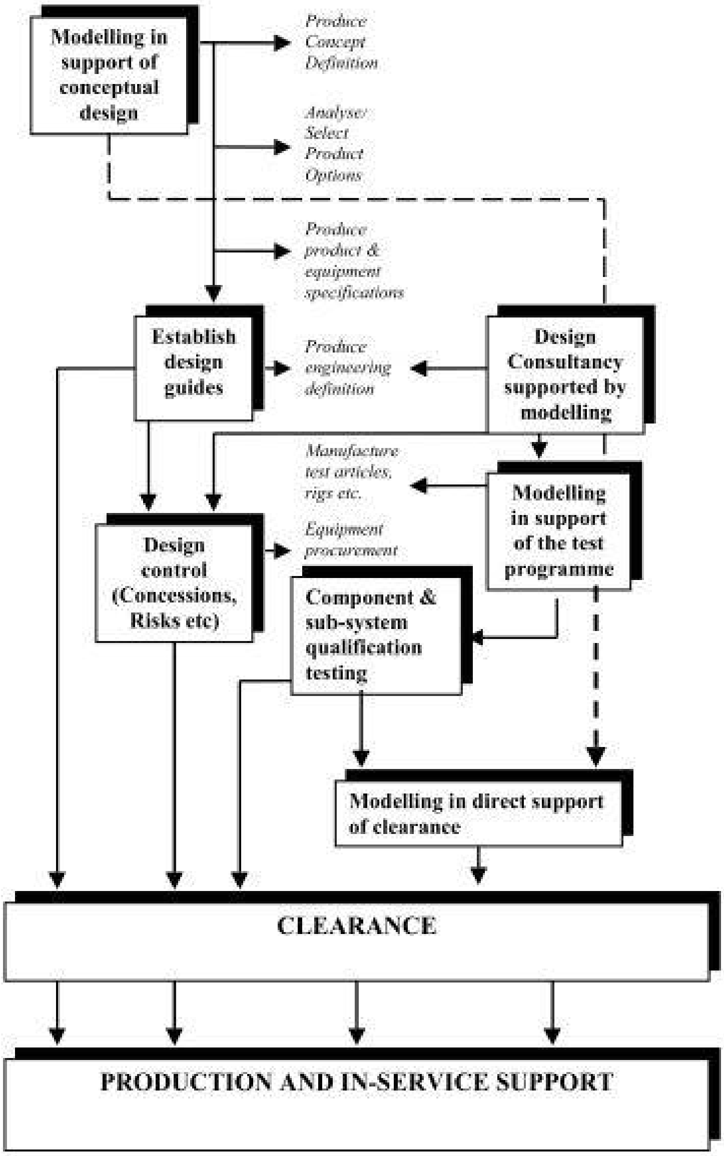

Figure 4: The Generic Design and Qualification Process for Battle Damage Tolerance.

At this stage it is possible to write meaningful specifications for equipment and components together with specific design guides which can be applied by non-specialist design and engineering teams. Inevitably design conflicts arise these are solved by an alternative design approach, often based on detailed modelling of the circumstance or a deviation from the design guidance which must be recorded and justified. In the case of Electromagnetic Hazard design, laboratory based equipment testing is in some cases combined with results of sub-system test results and finally the results of whole aircraft testing. All this test evidence is combined with computational analysis and the design traceability of the design guides and recorded deviations and concessions to produce the portfolio of evidence to justify qualification.

In the case of damage tolerance resulting from conventional weapons, component and major assembly test evidence is the usually the majority of test evidence which can be afforded. Computational analysis is used to extrapolate this limited view of practical results to the whole aircraft and across a range of threats and circumstances.

4.0 DAMAGE REPAIR

In the past, damage repair schemes were based on generic guidance. As designs became more optimised and critical, more specific guidance was required and the concept of repair manuals emerged. These were associated with a particular platform product.

The emergence of highly optimised composite airframes and extensive critical systems functions has resulted in a need for intelligent, knowledge-based, repair guidance. Furthermore the damage mechanisms have become more complex and the diagnosis of the extent of damage is a more subtle and complex task, often requiring NDT techniques rather than relying on visual inspection.

The philosophy of in-service repair must be considered from the earliest design stages in order to create a platform which is as repairable as possible in the field. This is a difficult area to specify precisely and as a result is difficult to review in terms of progress towards meeting the requirement through the project design life-cycle. Because of this there is a danger of it being ignored.

A further difficulty arises from the fact that a civilian engineering staff is possibly not ideally placed to determine the philosophy of battlefield repairs. It is suggested that a joint team of military and civilian personnel best determine this. The new approaches of "Capability Partnering" as used on Nimrod MR4A will help to overcome these issues.

A recent development in weapon system procurement is the contractorisation of through-life support. This has placed the potential for rewards arising from improved repairability right back with those charged with supporting the platform. If the prime contractor for the design and development of the platform has ambitions for through-life support then they will reap the rewards of investment in this area. The danger arises in the competition for such contractorisation. Bidders who do not understand the costs of supporting a particular platform or capability can submit apparently attractive bids, only to fail, perhaps at a critical time in a campaign.

5.0 THE BALANCE OF INVESTMENT ACROSS SURVIVABILITY

For some time the balance of investment across the range of properties that contribute to damage avoidance (see Fig. 1) has been debated. There has been some progress in this area although more refined work is necessary to achieve a satisfactory answer.

A number of problems arise in attempting to come to an answer. These include the sharing of very sensitive military data across a team of analysts who necessarily must include industrially-based personnel who understand configuration design, installed system performance and most importantly costs. The team must also include military personnel in order to have a full understanding of practical military tactics and usage. It can be seen that the difference in philosophy, combined with sensitive data, both military and commercial, makes a holistic treatment of the problem of balance of investment very difficult.

These problems are greatly exacerbated when attempting to achieve a balance across the three major elements of Survivability (avoidance, tolerance and repair) in which military philosophy must be mixed with industrial business thinking, together with complex, multi-disciplinary engineering and competition sensitive data often prior to bid compilation and submission.

It has been mentioned earlier that some of the changes that have occurred have caused a better understanding of the costs involved. However, there is still a considerable way to go, particularly in terms of rapidly assessing options and achieving a balance across Survivability in its entirety. There is considerable uncertainty with regard to the costs associated with damage repair.

One way of easing this problem is to carefully consider the procurement process from the viewpoint of establishing joint industry/customer teams for those activities that would benefit from this joint view, produce an output which could then be studied competitively and a response made. "Smart procurement" attempts to follow this philosophy, however, further thought is needed in the field of Survivability to address visibility of commercially and militarily sensitive information.

6.0 LEVELS OF MODELLING

Fig. 5 (Ref.2) shows the three major areas of modelling used to arrive at philosophy for the Survivability of an air platform. These are:

1. Combat simulation
2. Vulnerability analysis
3. Base Simulation

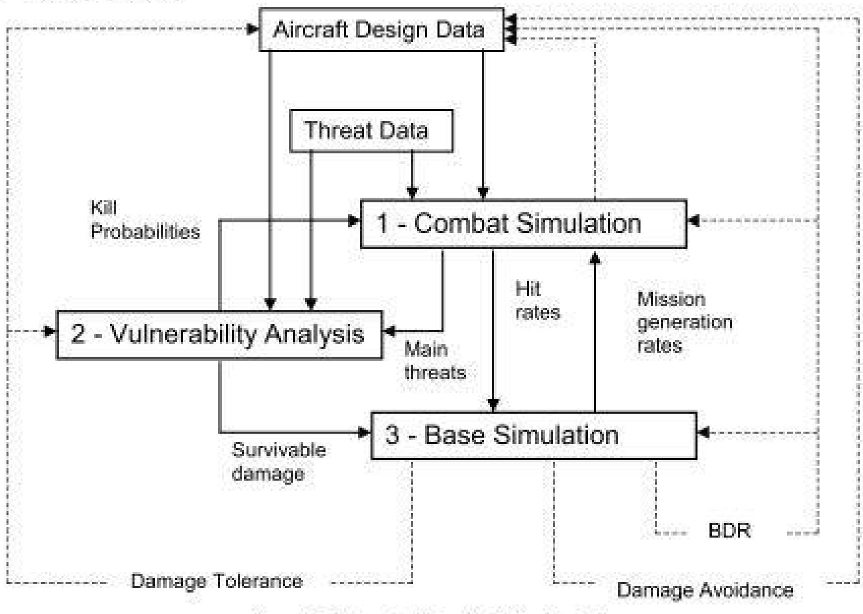

Figure 5: Integrated Survivability Analysis

The combat simulation is provided with data about aircraft design, threats and kill probabilities and produces "hit rates" and provides a view of the main threats. These feed the Base Simulation and the Vulnerability Analysis respectively.

The Vulnerability Analysis produces kill probability and the extent of survivable damage.

The Base Simulation provides Mission Generation data and as a result can produce information which allows exploration of battle damage repair philosophy, damage avoidance approaches and the extent of damage tolerance all in the context of the success or otherwise of the campaign.

It can be seen that this is a complex inter-linking of high level models, best managed from both an industrial and military viewpoint.

7.0 THE IMPLICATIONS OF NETWORK ENABLED WARFARE

The abstract briefly refers to the implications on Survivability, of "network-enabled warfare". One way of thinking about this is shown in Fig. 6 (Ref. 3). The majority of this paper to this point has considered the Survivability of a battlefield asset in isolation. In this case a military aircraft. In future conflicts such assets are unlikely to be operating outside a huge network supporting the objectives of the operation of such assets. This will change the balance of investment across damage avoidance and damage repair (since a similar picture can be drawn for logistics support) and a re-assessment is required for existing assets. Furthermore, a broader viewpoint encompassing this new dimension must be taken for optimising the balance of investment for new platforms. From the platform suppliers view the majority of this dimension of the "avoidance" problem space is GFE. We must not fall in to the traps created in the past as a result of the use of GFE (e.g. unclear performance measures, unhelpful boundaries of responsibility and a lack of a control framework over the entire problem of provision of a known war-fighting capability).

It can be seen from the diagram that "data links" appear at two levels in the network but their Survivability issues are the same. It is considered in this diagram that the sub-command facilities are likely to be relatively mobile, with all the "avoidance" benefits that can bring. This is not true for the Command Facilities. Both facilities must include in their "hardening" philosophy a consideration of the growth in the emerging information warfare possibilities.

8.0 CONCLUSIONS

The paper indicates how the approach to Survivability has changed for the prime contractors (and customers) of air platforms. The prime contractors are taking on more risk than previously and investments have had to be made to contain that risk.

In order to further improve the way in which Survivability is addressed, a number of further changes needs to be made. Attainable and verifiable requirements need to be developed, often in joint military and industrial teaming environments. Routes to qualification need to be agreed prior to contractual commitment.

Through-life costs of Survivability need to be understood, once again from the dual perspective of industry and the military users.

Finally the added dimension of network centric warfare needs to be explored. This is an added complexity that could provide some new approaches to improving Survivability.

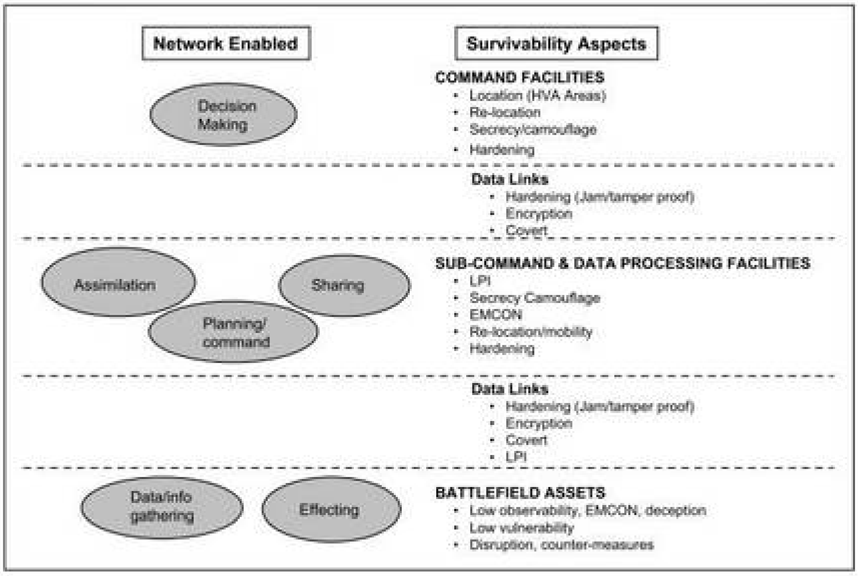

Figure 6: The Added Dimension of Considerations for Network-Enabled Warfare.

9.0 REFERENCES

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[2] M. Pywell, M.E. Hurricks, I.G. Wellings, "The New Enigma: Increased Survivability with Reduced Cost?", NATO RTO SCIP Symposium on "Flight in a Hostile Environment", 1999.

[3] Internal note from C. Lee, BAE SYSTEMS, Air Systems, Warton, UK.

10.0 ACKNOWLEDGEMENTS

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SYMPOSIA DISCUSSION – PAPER NO: 4

Discusser's Name: Barsoum

Question:
Would you please comment on the damage resistance of composites compared with aluminum?

Author's Name: MacDiarmid

Author's Response:
Composite materials bring benefits but like everything they have disadvantages. The disadvantages can in most cases be minimized by designing them for their specific use and the environment that the article will be used in.

THE NEW ENIGMA: INCREASED SURVIVABILITY *with* REDUCED COST?

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ABSTRACT

A U.K. perspective of the enigma facing Air Forces and military aircraft manufacturers is given. That is, how to increase aircraft survivability, to ensure improved war-time availability, whilst simultaneously meeting the increasingly strict affordability levels dictated by Defence Ministries and mandated by competition for military business world-wide. Issues of relevance to Air Forces, Defence Ministries and Industry are considered, and historical and current approaches to assuring appropriate aircraft survivability levels are discussed. The technologies, processes and procedures needed to ensure aircraft have the highest practical survivability against wartime threats, with sufficient robustness to tolerate likely peacetime damage, are outlined. An innovative approach to optimising the trade-offs between vulnerability, survivability and affordability is described. Survivability process enhancements and the way ahead are proposed. Three keys to resolving the enigma are seen:

- Conduct integrated survivability analyses as described herein.
- The Military, the Defence Procurement Agencies, their Technical Advisors and Industry must work ever closer and ever earlier together to ensure that requirements, designs and implementations are sound, feasible, survivable and affordable.
- Decrease aircraft vulnerability - make them capable of repair and return to the fray - don't lose them.

1 INTRODUCTION

1.1 OVERVIEW

This paper discusses the increasingly popular but complex topic of 'Survivability', the often un-quantifiable trade-offs between its constituent and inter-related components, and the issues surrounding resolution of the enigma of how to simultaneously increase survivability and reduce costs. A high quality perspective is believed to result from the unique grouping of authors[1], who together have extensive knowledge of the design, development and in-service use of various military aircraft types. Their experience base ranges from operational requirements definition and analysis, through research, systems design, air vehicle specification, systems integration, ground test and flight test, to operational evaluation and in-service use. The authors Pywell, Hurricks and Wellings are the U.K. Representatives on the 1998/9 NATO Research and Technology Organisation Study SAS-11 *'Requirements and Options for Future NATO Electronic Warfare Capabilities'*, currently in the reporting phase. The fourth is Chairman of both Eurofighter and Nimrod MRA4 Survivability Working Groups.

The background to this paper is a theme of constant change: conflicts are becoming more common - often with tighter Rules of Engagement (RoE's); there is increasing threat lethality; aircraft technical capability and complexity increase to compensate; and consequently aircraft, fleet and war costs rise. The need for increased complexity and cost reduction poses a major challenge for the Military, the Defence Procurement Agencies and Industry alike. This paper outlines the enigma, covering historical cost control, historical survivability developments and today's priorities. Modern and future warfare is described, comprising airpower – survivability in context, the changing nature of the threat and evolving requirements, and the importance of survivability during wartime. Typical survivability mechanisms, *i.e.* what could be done, are outlined for the areas of damage avoidance, tolerance and repair. Design control issues are discussed, *i.e.* what should be done. Cost control, *i.e.* how it has been and will be done, is covered. Finally conclusions are drawn and 'way ahead' issues proposed.

This paper is but one aspect of efforts by British Aerospace (BAe) and the U.K. Defence Evaluation and Research Agency (DERA) to fully satisfy military Customers' requirements - Affordability, Lethality, Flexibility, Availability and Survivability (ALFAS).

[1] Mike Pywell, Electronic Warfare Systems Specialist, Survivability Team, R&T Project, BAe. Paul M. Alonze, Vulnerability Specialist, Operational Analysis Discipline, BAe. Maurice E. Hurricks, DERA Farnborough, Weapon Systems Sector, Airborne EW Group, WS5A: Head of ESM and SEAD. Ian G. Wellings, DERA, Malvern: Future ISTAR Group - formerly EW1 (RAF), U.K. MoD.

Paper presented at the RTO SCI Symposium on "Flight in a Hostile Environment", held in Solomons Island, Maryland, United States, 19-21 October 1999, and published in RTO MP-47.

Together, the DERA and BAe's Research & Technology (R&T) Project:

- harness science and technology to ensure that Britain's defence and security services maintain their superiority – always.
- generate new and innovative technologies to solve military problems, conducting studies as appropriate to gain and enhance understanding of the associated operational benefits.
- conduct trade-offs to derive cost and effectiveness estimates of technological options for military solutions.
- investigate those technologies and, when mature, pass them over for Project adoption.

1.2 TERMINOLOGY

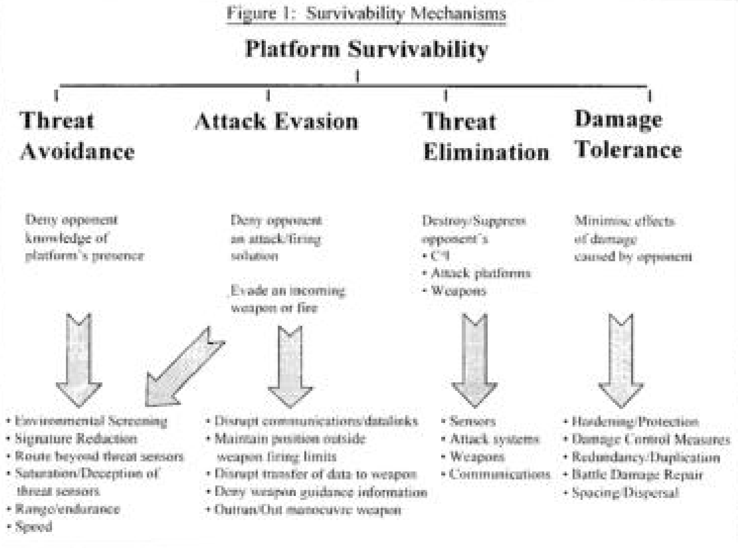
<u>**Survivability**</u>: It is necessary at the outset to define the term 'Survivability' and its constituent components, as there is a variety of opinions as to the scope and meaning of each. It is also important to understand at the outset that the term 'costs' means 'Life Cycle Costs' (LCC) and applies, dependent upon context, to individual aircraft or the fleet. Survivability is a measure of an aircraft's (or system's) tolerance and persistence within a given environment. Military aircraft survivability is traditionally specific to wartime operations and with regard to man-made threats. Safety-related survivability (*e.g.* bird strike, lightning strike) during peace and wartime is considered at the aircraft design stage but is not explicitly discussed in this paper.

Survivability against man-made threats can be achieved by one or a combination of several mechanisms, see Figure 1. These include threat (engagement) avoidance; attack evasion (given an engagement); threat elimination (before or during an engagement); and damage tolerance (after an engagement), which includes damage repair. Note, a wide variety of terms currently exist to categorise and structure these mechanisms. Such terms are often ambiguous and tailored to suit a particular domain or viewpoint. For the purpose of this paper we have chosen to adopt the following terms:

- **Battle Damage Avoidance (BDA)** – Use of measures to either prevent a threat initiating an engagement, or given an engagement, the use of measures to prevent the attack having a direct impact;
- **Battle Damage Tolerance (BDT)** – Given a direct impact, this is the use of measures to limit the effects of any damage and to enable the aircraft to continue to perform its mission;
- **Battle Damage Repair (BDR)** - Use of measures to restore an aircraft's ability to perform further missions.

<u>**Effectiveness:**</u> This term is used in the context of the capability of an operation, one's own or the opposition's weapon systems, and in countermeasures to threats. Various opinions exist as to the meaning of the term in each context, *e.g.* Combat Effectiveness is the normal measure of superiority over the enemy. There is believed to be a consensus that precise quantification of effectiveness in any context is exceedingly hard, if not impossible, to achieve. For the purpose of this paper effectiveness is taken in the EW context, where it is a measure of the ability of an EW system to ***adequately*** defend the aircraft against a given threat. Even in the EW context, it is very difficult to measure or quantify absolutely as there are many complex and interacting input variables, not least of which are EW tactics, which are often an integral part of the countermeasure. Ref. [1] contains a useful discussion of this point.

Figure 1: Survivability Mechanisms



2 OUTLINING THE ENIGMA

This section outlines the enigma, historical survivability developments, historical cost control and today's priorities. The enigma can be stated as: ***'How can aircraft survivability be increased, to ensure improved war-time availability, whilst simultaneously meeting the increasingly strict affordability levels dictated by Defence Ministries and mandated by competition for military business world-wide?'*** The importance of survivability is unquestionable, it is a key factor with respect to (in particular) air warfare and can significantly affect the operational efficiency and plans of any armed force. The importance of cost can be seen if the enigma is expressed slightly differently:

- Without a well-defined threat, with shrinking defence budgets, without 20-20 foresight and with a multitude of technical possibilities and innovations, how can Industry ensure that the Customer can procure an effective but affordable defence?
- Fewer numbers of aircraft procured increases unit costs. So we want increased survivability and mission performance at reduced cost but are procuring less aircraft. When do these criteria meet?
- What dominates the cost of stabilising survivability against more potent threats or increasing it against existing threats? Is it the provision of LO or enhanced Electronic Warfare (EW) systems or reduced aircraft vulnerability, or a balanced mix?

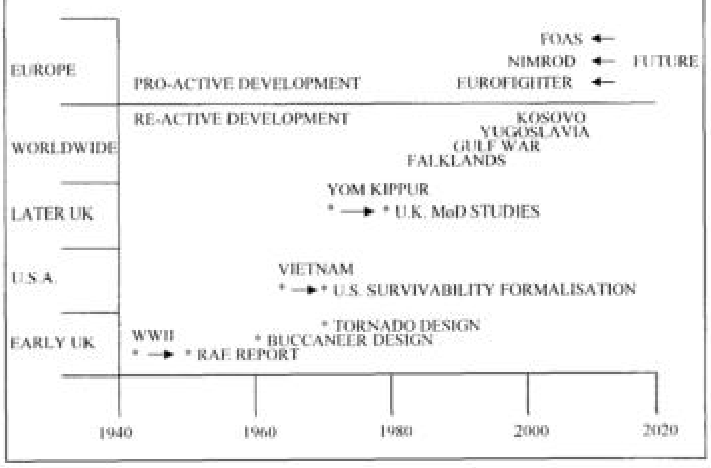
2.1 HISTORICAL SURVIVABILITY DEVELOPMENTS

Developments have often resulted from negative experiences in war fighting. This development has tended to be reactive. World War II efforts on survivability consisted of spontaneous design changes to install protection measures such as armour and fire suppression. The major milestones in the development of survivability as a discipline have, apparently, always resulted from the consideration of recent conflicts as indicated on Figure 2 (developed from [2]) and the main developments have resulted from three major conflicts.

The World War II losses were assessed by the U.K.'s Royal Aircraft Establishment (now DERA) and the lessons presented in technical recommendations on ways to design aircraft for low vulnerability. These guidelines were followed in the Tornado design and an appraisal of the Buccaneer indicates that this design complies with the DERA guidance.

Vietnam cost the U.S.A. in material considerations alone, a total of around 5000 lost fixed and rotary wing aircraft. The Americans thus learned a great deal about the need to reduce vulnerability, which caused them to examine aircraft vulnerability as the U.K. had done earlier. The U.S.A. coined the term 'Survivability' and gave it a high profile, making the discipline a comprehensive part of the aircraft design process. Middle East conflicts in the 1960's and 1970's showed how fast and intense a modern conflict could be, reinforcing the value of low vulnerability and highlighting the importance of fast BDR. There was much effort on BDR in World War II but not with the same urgency. Middle East experience illustrated that the great value of BDR remains even in modern conflicts. This demonstration of BDR as a force multiplier prompted other air forces to examine it as a formal part of their operating policy.

Figure 2 : The Reactive Development of Survivability as a Discipline



During the Gulf War, F-117 aircraft, the so-called 'Stealth Fighters', were used to attack and destroy key command and control centres. All aircraft returned unscathed. In so doing they demonstrated for the first time the benefits of stealth technology. These benefits were seen again in Operation Deliberate Force in Bosnia in 1995 under somewhat different circumstances. However, as the recent conflict in Kosovo has demonstrated, the failure to take a holistic approach to survivability can result in the loss of even stealthy aircraft.

2.2 HISTORICAL COST CONTROL

U.K. Industry has, in its business origins, the traditional strengths of technical excellence and innovation. This resulted from the old 'Cost Plus' contract conditions which ensured primarily the technical competence of the product which, in the case of aircraft, included survivability enhancement technologies. However, U.K. Industry also had a historical disadvantage, that costs were of secondary importance. The capability was all important - a 'failed' capability was seen to be worth nothing. The Customer paid the cost (whatever it was) plus a reasonable profit. This did not help develop effective cost control systems and cost consciousness in product design - cost control was not a priority. In recent years, the U.K. Ministry of Defence (MoD) has moved rapidly from 'Cost Plus' contracting to Firm, Fixed Price contracts with Installed Performance guarantees. This has obvious cost control benefits, but experience has shown it to be a double-edged sword. For Industry, building to a price is a driver for innovation but it adds commercial risks to already challenging technical problems. For the Military and Defence Procurement Agencies it poses three difficult (intractable?) problems:

1. Future requirements must be <u>precisely defined</u> for 20-30 years ahead.
2. Specifications must be <u>unambiguous</u>.
3. Solutions <u>must be flexible enough</u> for the changing world we live in - Items 1 and 2 do not give this.

The consequence of the above often results in 'extreme worst case' scenarios being defined to ensure robustness. This leads to extremely demanding requirements which, if unchecked, result in classical 'gold plated' design solutions - high performance at high cost.

2.3 TODAY'S PRIORITIES

The world-wide Customer (Air Forces, MoD's and their Technical Advisors) have identified cost and survivability as major drivers; increased survivability <u>and</u> lower cost are seen to be essential. Industry could be forgiven for saying "Is that all?" - indeed, this is not the way Industry normally operates. For each aircraft there is a multitude of operational and design requirements, of differing levels of importance, which have to be traded against each other and against cost before an affordable, survivable and realisable product can be agreed.

For Industry the challenge thus appears to be ever increasing. There are greater technical constraints and greater competition than ever before, and there is a greater need for effective military support. Industry thus has to provide better, more effective, tailored products. In turn this means determination of the best complementary technologies, careful evaluation of the actual benefit of the range of survivability enhancement techniques available, and a need to be innovative and prognostic. There are also commercial drivers, which nowadays have greatly elevated importance. There is a need to understand technical and cost factors and risks throughout the process. This mandates closer working with the Customer, detailed Risk Identification, Management and Mitigation activities, and a level of openness, honesty and process transparency previously unheard of.

In the U.K., this new approach is beginning to take shape following the Government's Acquisition Organisation Review and Smart Procurement Initiative (SPI). The review carried out a fundamental examination into how the MoD procured equipment and how it was organised to do so. It identified the following reasons for change:

- Less predictable threats and tasks
- Increasingly complex and diverse defence equipment
- Changing industrial structure
- Continuing time and cost overruns which currently exceed the new Treasury performance targets

The SPI was born out of this case for change and has established a programme to address these issues. A key concept of SPI is that of an Integrated Project Team (IPT) which is defined as: 'A single integrated project team bringing together all stakeholders and involving industry except during competition phases'. A number of Pilot Project teams (*e.g.* FOAS, Nimrod MRA4) were formed in the first half of 1999, and the remainder of the U.K. procurement programme is now in the process of implementing this new approach.

<u>3 MODERN AND FUTURE AIR WARFARE</u>

This section describes the 'living' requirement driven by the ever-changing face of conflicts around the globe.

3.1 AIRPOWER – SURVIVABILITY IN CONTEXT

To understand the relative importance of the many possible trade-offs between the components and sub-components of survivability, it is first necessary to understand the role of air power and its fundamental characteristics. Air power, as defined by the RAF [3], is the ability to use platforms operating in or passing through the air for military purposes. The means of exercising air power are many and include any system which can be used to wage warfare in the air, *e.g.* manned and unmanned aircraft (fixed and rotary wing), guided missiles, balloons and space vehicles. Air power's characteristic strengths include: height; speed; reach, ubiquity (within given resources); flexibility; responsiveness; and concentration of military force. Its inherent limitations, on the other hand, include impermanence (cannot stay airborne indefinitely), limited payload, and fragility. Furthermore, airpower possesses other well known characteristics: dependency on bases; sensitivity to light and weather; and sensitivity to technology. Survivability, or to be more exact, survivability mechanisms (see Section 4) aim to exploit some of these strengths (*e.g.* height, speed) and minimise some of the limitations (*e.g.* fragility). The key issue, however, is determining the balance and how to achieve a cost-effective solution that is robust to a changing threat.

3.2 THE CHANGING NATURE OF THE THREAT AND EVOLVING REQUIREMENTS

To determine the force and aircraft mix requirements to support a given war or campaign in a given time frame, military planners consider an extensive range of aspects. These include:

- geo-political scenarios
- strategic, operational and tactical objectives
- RoE's
- own, allied and opposition capabilities and vulnerabilities
- current and planned asset and capability availabilities
- threat countermeasures
- asset introduction, enhancement and retirement timescales and affordability
- planned and allowable attrition[2] rates
- main/forward base logistics requirements/capabilities

From these considerations arise a number of force mix options which are further analysed to arrive at the most operationally- and cost-effective planning solutions to a list of perceived current and future scenarios which satisfy military/political objectives and constraints with an appropriate margin of safety and which also provide an appropriate back-up/contingency plan.

For national and international military planners, *e.g.* those of NATO, the above considerations are a continuous process, particularly as the nature of the threat is constantly changing and evolving. This change and evolution can be demonstrated best by considering the move in recent years from considering the bulk of military operations to be of the Article V type[3], to a predominance of the NATO Peace Support Operations (Keeping and Enforcement) types[4] where political constraints often result in restrictive RoE's even in high hazard areas. Furthermore, the increased political sensitivity to loss of military personnel and civilian casualties has led to a profound strategy shift. This has resulted in the need for minimum collateral damage and a shift to 'near zero' attrition philosophy of own forces.

The above process and shift in strategy lead to the requirements for new and upgraded air/sea/land weapon platforms and systems. In these times of stringent military budgets it is increasingly important for Industry, who often tend to be rather product-focused, and the Military to work closely together to explore all possible force mix solutions. Moves to this effect are growing in Europe and are reasonably well advanced in the U.K. It can be argued that neither party in isolation has a full enough understanding of (in general) all the ALFAS trade-offs and (in particular) all the survivability component/sub-component trade-offs. For example, it is hard to quantify and justify the case to purchase an Escort Jammer for a raid package rather than accept a potentially higher attrition rate (*e.g.* buy an extra raid package aircraft) with the survivability of individual aircraft being increased by fitting each with an enhanced EW suite.

3.3 THE IMPORTANCE OF SURVIVABILITY DURING WAR TIME

Survivability has a major impact on sortie generation capability during wartime and fleet size for a given conflict, battle, campaign or war, and thus directly affects fleet LCC. A modern large scale conflict (*e.g.* NATO Article V) might start with an intense initial period where heavy losses will be sustained, see Figure 3, and fighting effectiveness consequently reduced. This

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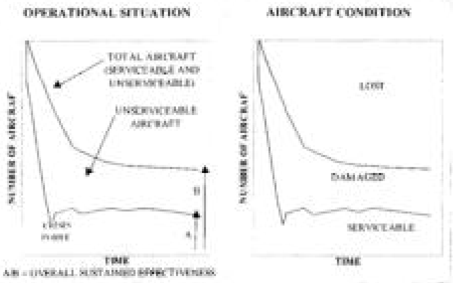
[2] Attrition is a real world factor used in fleet sizing calculations. It is the number of aircraft destroyed or damaged to such an extent that they are irreparable in the timescale of the battle, campaign or war (whichever is being considered). The damage or destruction is by whatever means, whether caused by *e.g.* lightning strike, equipment failure or ground collision *en route* to the battle/target, or in combat. For any mission, it is predicted and then its operational and/or political acceptability considered. It is a characteristic that indicates the level of survivability achieved, in effect the 'measure' of survivability = (1-Attrition). Highly survivable aircraft will exhibit low attrition.

[3] Article V: 'The Parties agree that an armed attack against one or more of them in Europe or North America shall be considered an attack against them all…' and that they shall assist the Party so attacked to reinstate the *status quo* prior to the attack.

[4] Peace Support Operations (PSOs), as defined by NATO, are composed of the following six different operations: Conflict Prevention; Peace Making; Peacekeeping; Humanitarian operations; Peace Enforcement; Peace Building.

Figure 3: Aircraft Losses from the Generic Intense War



generic curve reflects historical experience by showing how the numbers of available aircraft will reduce rapidly and how a significant proportion will be damaged. The damaged aircraft will be out of action for most of the conflict due to normal repair timescales. Since the accumulative damage and loss rates could be very high, aircraft availability is critical.

This emphasises the need to avoid damage as far as is practical and the equally important need to conserve and re-cycle valuable damaged aircraft. It is essential that damaged aircraft can return to base and can be repaired quickly. Remembering that the purpose of the aircraft is to generate successful combat missions, survivability is fundamental to this aim. Using survivability techniques to extend aircraft operational life increases the fleet's capability and so survivability can be considered to be a true force multiplier.

Looking at recent conflicts and the problem of losses - even for low intensity 'peace keeping' operations - losses must be minimised - to avoid the withdrawal of public support and/or disintegration of multi-nation alliances. The 'near-zero' attrition philosophy mentioned earlier mandates Maximum Survivability – a feat yet to be achieved anywhere on any platform.

The level of damage and loss shown in Figure 3 in the intense phase reflects the typical Cold War type scenario which, whilst not strictly aligned with modern regional conflicts, does represent an essential worse case for design. To design for a lesser case could lead to danger that a return to a Cold War, possibly against a future power in twenty years time, could leave us with aircraft not capable enough to deal with the challenge. Who knows, twenty or thirty years in the future, who will be the enemy, how likely a new Cold War would be and how intense a conflict could become? Under these conditions a typical intense conflict (a full scale war) could produce very high loss rates, a great reduction in aircraft availability and an early crisis point where the force is at its lowest ebb and the point at which the war could be lost. Together these issues pose another enigma – do we design high performance (and high cost) aircraft capable of handling this speculative distant future 'Article V'-type threat, or do we constrain our detailed requirements and specifications to the near term threat (say 5-10 years ahead), which may be cheaper but could be impotent?

4 TYPICAL SURVIVABILITY MECHANISMS (WHAT COULD BE DONE)

Survivability against man-made threats can be achieved by one or a combination of several mechanisms, see Figure 1. These include threat (engagement) avoidance; attack evasion (given an engagement); threat elimination (before or during an engagement); and damage tolerance (after an engagement). These mechanisms can be realised through a variety of approaches; some technology-based, others tactics- and doctrine-based. This section covers typical solutions which are or may be available to assist in the quest for increased survivability. The contribution of various topics *e.g.* EW, LO and improved damage tolerance, to ensuring - or, more realistically, at least improving - survivability is addressed. The latest requirements of the Customer, world-wide, show the trend towards adopting the principles of Inherent Survivability, *i.e.* all components of Survivability should be enhanced by features incorporated in the basic design. Survivability requirements are becoming more important to air forces around the world. LO, Low Vulnerability and BDR preparations have been included in formal requirements and these have been aimed at increasing mission generation rates.

Improvements in Survivability mandate improved technologies, designs and design methods. Typically the technologies that can substantially enhance Survivability, *e.g.* LO and EW, have to be new and/or innovative to supply the superior feature or performance required. Each major technology has the ability to impact cost significantly - LO is a good example. The individual and relative benefit, design implications, risk and cost of each technology and design change must be fully understood and traded to arrive at a final solution. However, the hasty insertion of immature technology into a Project can by itself create serious programme and cost difficulties. The regulated development of technology, using maturity gates to evaluate the success of each stage of development is a good way to check and control the necessary advances. The transition, see Table 1, from Blue Sky (brand new) to White Cloud (developing) to Green Field (ready for implementation) illustrates the graceful capture, control and 'soft landing' insertion of new technology. Once the operational benefit of each technology is proven, the technology mastered and under control, and the cost and life cycle implications understood, Industry is able to commit the technology to projects. The range of available and potential technologies is large and could provide a legion of possibilities. Care must also be taken that in the likely multi-threat environment, where 1st through to

5th generation threat systems could be encountered - protection measures must have 'complementary' effectiveness. That is, protection for 5th generation systems must not unacceptably increase risks posed by 1st generation systems.

Table 1: Technology Spiral – Transition to Projects

	Risk : Cost	Competitive Edge	Benefit
Blue Sky	High : Low Cost	High	Positioning
White Cloud	Moderate : High Cost	Moderate	Potential
Green Field	Low : High Return	Low	Real Investment

The potential benefits of enhancing each survivability component can be illustrated by looking again at the operational picture (Figure 3) where the original fleet is divided into aircraft in one of three states: lost, damaged or serviceable. This type of generic figure is now used to illustrate the general nature of theoretical enhancements.

- Lost Aircraft: The drop of the top line shows the rate of aircraft loss (5% is often treated as acceptable, but several conflicts have seen much greater rates). The top area thus indicates the aircraft lost – this needs to be minimised.
- Damaged: The middle area are those aircraft not serviceable either through battle damage (the main reason in wartime) or reliability failures. Ensuring that the aircraft can tolerate damage, to reduce losses, increases this area.
- Serviceable: Aircraft in this area are capable of carrying out operational missions. This is in effect the fighting strength of the fleet.

This Figure can now be used to illustrate the benefits of various enhancement techniques. It is necessary to understand the ability of certain design features (the damage avoidance, damage tolerance and damage repair elements) to work together to improve overall operations. This could well represent the operational capability of an early conceptual design - without the benefits of major enhancements. The bottom area is the one that matters - this is the actual fighting asset available and thus the area needing to be maximised using specific design features. The design features come from three generic improvement areas: Damage Avoidance, Damage Tolerance and Damage Repair - noting that 'Damage' is that caused by enemy action, *i.e. Battle* Damage. Moving from the baseline situation the potential benefits can be visualised in terms of increasing the operational strength of the fleet. Three primary options can exist, either singly or in combination and these are described next.

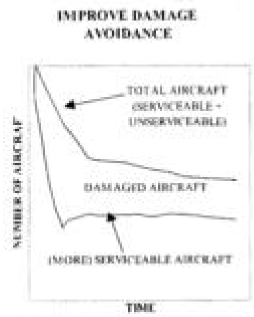
4.1 DAMAGE AVOIDANCE

Survivability enhancement through damage avoidance is discussed, followed by a set of technology options for increased survivability. Adoption of one or more of these leads to improvements to the damage avoidance component, which in turn will elevate the 'Total Aircraft' and the 'Serviceable Aircraft' lines on Figure 4, giving an immediate operational benefit due to the increased number of undamaged aircraft. This figure assumes that the aircraft have a reasonable level of damage tolerance to enable them to return to base when hit. The maximum potential has not been achieved, however, since there are still damaged and lost aircraft. This is therefore only part of the way towards a Zero Attrition Philosophy. Further improvement is then possible by using enhancement techniques from the damage tolerance element, discussed in the next section.

4.1.1 Damage Avoidance Enhancement

This can be achieved by reducing aircraft ***Observability*** (the aircraft's ability to minimise any chance of interception by enemy forces) and/or ***Susceptibility*** (the openness of the aircraft to being hit). The former can be attained by ***Avoiding*** or ***Evading*** detection and engagement by threat weapon systems. The latter can be attained by increasing ***Situation Awareness*** (and thus increasing the options available) and/or ***Threat Neutralisation/Elimination*** capability.

Figure 4: The Effect of Improving Damage Avoidance



Threat Avoidance/Attack Evasion has the following two components. Of note is the fact that usually for attack missions, other than those using stand-off weapons, avoidance/evasion is temporary - eventually the aircraft has to go in harm's way to achieve the military objectives.

- Multi-spectral LO, comprising suppression of own basic signature ('passive' LO), and temporal, spectral and spatial control of own deliberate Radio, Radar and Electro-Optic (RF/EO) transmissions - EMCON (Emissions CONtrol). Passive LO includes audio and visual signatures in addition to the more common Radar Cross Section (RCS) and Infra-Red Signature (IRS) used in the definition of EW countermeasures.
- Routeing, speed, altitude, manoeuvrability and tactics, which includes terrain masking for low level flight, and where the latter two topics are predominantly aircraft type-dependent.

Situation Awareness is the acquisition, analysis and interpretation of knowledge of friendly and threats' dispositions. This can be achieved by use of on-board multi-spectral sensing systems - primarily passive, *e.g.* ESM, IR Search and Track (IRST), MWS and Laser Warner (LW); but also active sensors such as radar. Situation Awareness can be augmented by the receipt of multi-source off-board intelligence *via* communications systems or data links.

Threat Neutralisation/Elimination comprises:

- Suppression of Enemy Air Defence (SEAD), including Stand-Off/Escort Jamming (SOJ/ESJ), Hard Kill and Directed Energy Weapons.
- EW, whose aim is to reduce aircraft attrition and increase mission effectiveness through the use of an optimal Defensive Aids Suite (DAS) which includes the capability to defeat current and projected homing missiles.

4.1.2 Technological Options for Increased Damage Avoidance

Increases in survivability can thus be achieved by addressing each or a combination of the following. Some of the issues associated with each are mentioned.

Increased per-aircraft survivability which could be achieved *via* one or a combinations of these:

Reduced electromagnetic signatures (RCS, IRS, visual, audio and *via* EMCON): LO performance is a prime factor in the aircraft avoiding interception by enemy threat systems. An important problem for future combat aircraft is an increased understanding of the synergy and trade-off between LO and EW performance, especially in the light of increasingly tight RoE's[5] applicable to many operations, which often mean visual identification of a target before weapon release. A major issue is achieving satisfactory Jam-to-Signal ratio - in the case of DIRCM, for example, LO can be the key to performance. LO will, in the first instance, reduce the chance of being detected but, once detected, the aircraft signature level can be critical in determining the effectiveness of the countermeasure, whether RF or EO. Whilst valuable if successfully implemented, these LO features are, however, difficult to achieve and difficult to retro-fit to existing aircraft types, *cf.*[4]. They tend not to be operationally relevant or cost-effective unless an appropriate and often large level of reduction can be attained. As a survivability enhancement they are not usually relevant to certain, larger classes of aircraft (*e.g.* transports). LO features cost more, unless incorporated in the original aircraft design.

Improved DAS (EW equipment): This could take the form of increased EW functionality and/or performance, above the bare minimum suite, considered for many years to be a Radar Warning Receiver (RWR) and Flare/Chaff system. Arguably, nowadays, a minimum competent suite should also include Missile Warning System (MWS) and off-board ('towed') RF decoy. Better still, a comprehensive suite should have on- and off-board Electronic Countermeasures (ECM) and a modern Electronic Support Measures (ESM) in place of the RWR. DIRCM and towed EO and RF/EO decoys whilst not yet here for fast jet aircraft, offer further promise of survivability enhancement. Unfortunately, the inclusion of these additional capabilities, which also include digital receivers and increased flare/chaff capacity, all equate to increased cost. This is discussed in Section 6.4. Issues concerning enhancement of the primary threat warning system, RWR, are discussed later in this sub-section.

It is worth noting that the DAS tends to be a mission critical requirement, *i.e.* survivability is dependent upon correct operation of the equipment – system failure equals aborted mission. EW has also tended to be fitted as an addition when funds permitted in the past, which has usually meant sub-optimal performance. Designing it in as part of the overall system should improve its performance and hence survivability. To this end, as it is not possible to specify the operational requirements for the airframe life, the DAS needs to be specified with an evolution path in mind.

Other potential for EW-improved survivability includes co-ordinated (*via* the DAS) and co-operative (between platforms) ECM.

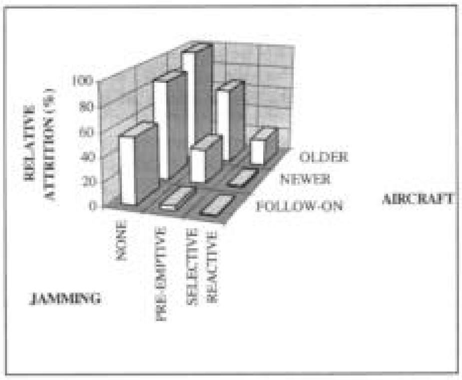
Better Situation Awareness: This could result from improved EW system Direction Finding (DF) capability, enhanced on-board sensor/data fusion and off-board sensor/data fusion (*via* data links), individually or preferably in concert. This is discussed in the Data Fusion and ESM paper [5].

[5] RoE's are related to technical capability, usually precision (or lack of it). Thus improved equipment should reduce these constraints, which sometimes lead to increased vulnerability.

<u>Increased *fleet* survivability</u> *via* enhanced support and adoption of a System of Systems approach. This is where the increase can be achieved through the use of an appropriate force mix in conjunction with appropriate joint strategy and tactics. This would typically comprise dislocation (destruction preferred) of the enemy air defence system first, to minimise the risk of having to face and counter the threat weapon systems later in the operation. Specific issues are:

<u>Suppression of Enemy Air Defence</u>: Recent conflicts have adequately demonstrated the benefits of early and sustained use of support jammers and SEAD 'hard kill' aircraft. Examples include Stand-Off and Escort Jammers, such as the EA-6B Prowler, the EC-130H 'Compass Call' communications jammer and the now-retired EF-111A 'Raven', together with 'Wild Weasel' hard kill assets such as the Electronic Combat and Reconnaissance (ECR) Tornado and F-16CJ with their effective mix of EW and High Speed Anti-Radiation Missile (HARM) capabilities. An indication of the benefits of support jamming can be seen on Figure 5 (adapted from [6]). In this Figure 'selective reactive jamming' means the jamming is changed if and when the threat radar parametric or operational characteristics change, and 'older', 'newer' and 'follow on' aircraft equate to 'older and non-stealthy', 'modern with smaller RCS' and 'stealthy' aircraft. Whilst Kosovo in particular demonstrated the high value of support jamming, it also highlighted the scarcity of support jamming resources available to NATO-led and similar multi-national operations. Whilst NATO and a number of nations are known to be seeking tactical jamming pod solutions to this problem, there remains a strongly held view, *e.g.* [7], that reactivation of the Raven is both viable and cost-effective.

<u>Figure 5:Impact of Support Jamming on Survivability</u>



<u>Command, Control, Communications, Computing and Intelligence Assets</u>: The contribution of these classes of Information, Surveillance, Target Acquisition and Reconnaissance (ISTAR) systems to the formulation of a Recognised Air and Surface Picture (RASP) for the effective control of air power, whether for temporary air superiority or enduring air supremacy, cannot be under-estimated. Assets available within NATO Nations include Airborne Warning and Control System (AWACS) such as the NATO E-3A, U.K. E-3D 'Sentry' and E-2C 'Hawkeye', Airborne Ground Surveillance systems such as the E-8 'Joint Stars' and the planned U.K. Airborne STand-Off Radar (ASTOR), and dedicated electronic reconnaissance aircraft, *e.g.* Nimrod R1 'Merlin', Bregeut Atlantic, EP-3E 'Aries II', RC-135 'Rivet Joint' and U-2.

<u>Improved Interoperability</u>: To assure optimal chance of survival, perfect interoperability is required between the multitude of international assets of all types present in the NATO-type operations typified by Operation Allied Force. As such, this mandates information interoperability, which in turn would rely *inter alia* on the effective use of very high bandwidth, secure data links of the type not yet fitted to all war-fighting aircraft. Such communication links thus become a survivability driver relative to off-board information.

At the RF level, this would also require resolution of some near-to-the-edge of the laws of physics problems - predominantly that of how to sense very small signals in the presence of very large in- or near-band signals generated on the same aircraft, by someone in the local formation, or by a ground or airborne emitter some considerable distance away from the sensor.

As accurate information with regard to the tactical situation from on- or off-board sources is instrumental in improving survivability, it should be possible to trade sensor capability against protection measures, both lethal and non-lethal, to achieve a given level of survivability.

<u>The Critical Importance of the RASP</u>: For increased survivability of war-fighting platforms, a *<u>precise and unambiguous</u>* RASP is required, with timely and accurate identification of threats to all war-fighting aircraft at risk. This is not presently possible for single- or multi-nation operations of the NATO-led type seen recently, *e.g.* Allied Force (Kosovo), for a combination of (primarily) technological and operational reasons. The major EW contribution to the fusion process, leading to the RASP, is threat RF emitter data provided by the passive detection RWR, ESM and ELINT systems, *cf.* [5]. The quality, accuracy and timeliness of this data is also critically important to aircraft survival, once flying in harm's way. The main issues are:

- The markedly different function and performance capabilities between (relatively cheap) RWR, modern ESM equipment and (the more expensive) ELINT systems, and between receiver types by different manufacturers. Such differences include sensitivity, scan methods (auto *vs.* manual) and DF accuracy.
- Installed performance differences, *e.g.* with same receiver type on same aircraft type, and with same receiver type on different platform types.
- The timely and co-ordinated use of common emitter data bases for the programming of threat parametrics into the RWR/ESM, ECM, Electronic Protection Measures and weapons, *e.g.* HARM and Air-Launched Anti-Radiation Missile (ALARM), of all friendly nations in theatre.
- Different tracks, orbit locations and altitudes of the various ESM/ELINT/RWR sensors in theatre.
- Different operator experience (ESM *vs.* ELINT operator, functional analysis).
- Geographic ambiguity (which can, to an extent, be resolved through triangulation).
- Radar ambiguity (including its intentions).
- Differences in Intelligence information.
- Threat detection and recognition performance differences between those seen in laboratory tests and those in theatre. (Due perhaps to a combination of imprecise equipment specifications and inadequate emitter simulation fidelity levels used in the EW development, test and evaluation processes.)
- The highly statistical and probabilistic nature of EW receiver system interaction with the real-world RF environment, especially in the case of fast jet aircraft.

Together with the inherent difficulties of unambiguous threat RF emitter location and identification in an electromagnetic environment almost saturated with threat and friendly RF pulsed and CW signals, the *reliable and timely* reporting of threats to all the hazarded war-fighters in theatre and construction of a precise RASP remains an elusive goal. The resolution of these issues is the focus of most NATO and Nations' R&T agencies.

The operational or technological rationalisation of EW receiver system performance in joint operations is thought a primary candidate for future R&T attention. Such attention should include answering the question *'Will upgrading/replacing the 'worst' EW receiver systems in NATO and similar joint operations and/or the introduction of more digital receiver based RWR's/ESM's to more platforms reduce this problem to an acceptable level?'*

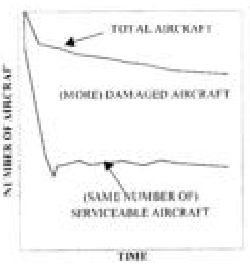
4.2 DAMAGE TOLERANCE

In some situations damage avoidance can fail and the aircraft suffers damage. Whether this results from the enemy's move to improved tactics, their fielding of a 'Secret Weapon', human error, an exhausted supply of decoys, or just the numerical superior of the enemy, damage tolerance is the insurance policy that prevents total loss of the aircraft. The intention of damage tolerance, the inverse of vulnerability, is to give the aircraft a basic level of robustness to ensure survival, primarily of the crew, when damage avoidance fails and the aircraft is hit. Appropriate design activity ensures the use of damage-tolerant materials and the duplication and physical separation of critical functions to help prevent any damage becoming catastrophic.

The vulnerability of the aircraft is a quality of the design and formal guidelines and requirements are normally documented in standards such as in the UK DEF STAN 00-970 'The Airworthiness and Design Requirement for In Service Aircraft' and DEF STAN 00-971, the equivalent for engines. There are many design features that could ultimately limit the maximum amount of damage that a new design could be expected to tolerate. The use of a survival conscious configuration for example is fundamental in eliminating many normal kill modes. This is done by ensuring that mutually antagonistic features are well separated. Fuel and fire raising agents would be separated for example. A mandatory vulnerability analysis of the aircraft is required in the standards and this normally evaluates the main design option to maximise the damage tolerance of the final aircraft. The design aim is normally achieved by evaluating the potential for incorporating these features: Damage-tolerant structure; Survival-conscious configurations; Redundant control systems; Graceful degradation of systems; Duplicated and separated critical functions; Crew protection; Fuel retention; Fire suppression; Damage-tolerant engines, and other Specific protection measures. The analysis serves to define the potential level of vulnerability likely and indicate what level of damage tolerance could be possible ultimately for the specific aircraft being considered. The actual vulnerability of the aircraft results from many factors and thus this multi-disciplinary work needs to lead to understanding of effects of damage to the flight and mission system, as well as the structural and aerodynamic performance of the airframe.

The important factor here is the timing of the analysis; when done early in the concept phase the necessary design changes cost very little and this hardness is incorporated at little or no cost. So whilst the above applies primarily to new aircraft design, many of the features can be retro-fitted to existing aircraft. The cost, however, is often difficult to justify as the trade-off between cost and survivability, as discussed earlier, is difficult to do at this time with any credibility. Examples of this difficulty include hardening the airframe/skin (which is difficult to retro-fit), selective replacement of 'soft' panels, EMC hardening and optical/RF sensor protection. Despite this observation, hardening aircraft to worthwhile levels can ensure that a larger proportion of damaged aircraft return to base and is thus of value. Although the area of damaged aircraft increases on Figure 6 this is in fact a benefit - the potential for repair and return to the conflict is far preferable to outright aircraft loss. This is important in saving the aircraft, raising morale and regaining the expensive assets even if the aircraft are too badly damaged and out of action for that conflict. Spare parts can be re-utilised during and after the conflict and this alone is a valuable factor. Whilst the vulnerability reduction activity gives benefits at this point, the protection and penalties that result do not give an immediate increase in aircraft availability or mission generation. As previously no immediate major operational benefit results - the bottom area on the figure is unaffected. An area of unserviceable aircraft remains however and so the potential is yet to be reached. Only when the final element of Survivability - BDR - is added, are all possible benefits gained.

Figure 6: The Effect of Improving Damage Tolerance



It is worth noting that damage tolerance applies, under the proposed 'holistic' or integrated analysis, to the Integrated Weapon System, which now includes the airbase and support facilities so essential for continued operation of the aircraft element of the System. Thus the damage tolerance of the support system is critical, as the main base, forward base or aircraft carrier is usually easier to hit than the aircraft.

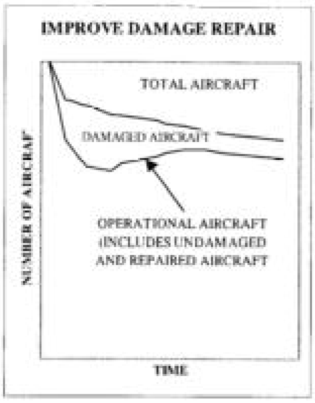
4.3 DAMAGE REPAIR

Repairability or Damage Repair (or more precisely BDR) is the ease, having sustained damage, with which the aircraft can be repaired. BDR requirements equate to wartime logistical support requirements. In an intense conflict attrition rates may be high and the ability to recycle damaged aircraft into mission capable standards could be critical to campaign success. BDR is an 'alternative engineering solution' aimed at returning damaged aircraft to mission capable state in minimum time, using quick and easy repair techniques, which mandate their definition and planning during the design process. Again the emergency repair of the airbase or aircraft carrier in minimum time could likewise be critical in enabling safe landing and regeneration of aircraft into the conflict.

The addition of an effective BDR capability returns damaged aircraft to operations and can boost the availability and mission generation rate significantly. The benefits of Survivability now pay off as the combined area of Undamaged and Battle Damage Repaired Aircraft lifts the operational line towards the total aircraft line multiplying the effective force. The faster and more capable the BDR activity, the greater the number of operational aircraft, the greater the mission generation and the more capable is the defence system. Survivability activity is aimed at enhancing wartime operations but the benefits extend to peacetime also, since a Survivable aircraft should be an inherently safer design. An effective BDR capability would include Damage Repair measures such as: modular design, standard (non-handed) parts, well-labelled pipes and wiring, accurate and easy to use BDR manual, and damage limits and repair advice prepared in advance. This would enable damaged aircraft to be rapidly recycled and put back into service.

The increased level of damaged aircraft that return to base because of reduced vulnerability are now returned to the fight and boost the bottom area in Figure 7. The speed of assessment and repair is critical in conflict timescales and BDR must be prepared in advance. Useful design features can be built in to the aircraft, systems can be identified clearly and information prepared to support the damage assessor on the ground. The latest Knowledge-Based Systems technology has recently been extended to enable a rapid assessment of damage and the quickest possible return to operations, by semi-automating the traditional BDR Manuals. Wartime spares can be predicted and stocked in advance, survivable damage can be predicted and schemes developed for generic levels of damage for specific application in the field. The damage assessment software can define alternative repair options and indicate the timescales involved. This provides the operational commander with the management information he needs to best match his available assets to the mission requirements. With this final element of Survivability in place, a much enhanced fighting force can be had, as can be seen by comparing Figure 7 with Figure 3.

Figure 7: Effect of Improved Damage Repair Capability



5 DESIGN CONTROL (WHAT SHOULD BE DONE)

5.1 ANALYSIS AS THE KEY TO CONTROL

Survivability is a complex multi-disciplinary subject that is difficult to measure - a pre-requisite of control. This begs the question of how to adequately represent the survivability of a range of candidate aircraft so as to determine the best solution? The use of a relatively simple Pk and Ps estimate[6] to define losses (attrition) cannot be considered as a 'holistic' process. Only by being able to represent and measure all facets of the survivability equation can survivable and cost-effective designs be achieved and traded against each other. Thus the integrated survivability analysis covers and unites three very different types of analysis:

- Combat Simulation - evaluating the BDA element.
- Vulnerability Analysis – evaluating the BDT element
- Base Simulation – evaluating the BDR element

The vast range of technological options provides a challenge to the military and industrial staff whose job it is to decide on the content and direction of military equipment programmes. It is also a challenge to the designer – to achieve the optimum technical and cost balance. To arrive at and then control such an optimum design, a broad analysis framework is required with the sophistication necessary to handle the wide range of parameters involved. The integrated analysis framework covers all the main elements of survivability in the context of the wartime scenario, to provide the ability to model their individual and interactive effects accurately enough to provide the high quality inputs to the cost estimation process. Such an analysis framework can be used to develop a 'holistic design' by assessing the fitness of the overall concept in its operational context.

The overall survivability analysis considers the Integrated Weapon System, which covers the flight vehicle, the weapons system and integrated ground support with the aim of maximising operational effectiveness. The Survivability Analysis can predict the likely operational life of an aircraft fleet in wartime and then investigate ways of improving wartime longevity. An description is now given of the major analysis stages and the data flow through the Combat Simulation, Vulnerability Analysis and finally the Base Simulation.

5.2 PROCESS – INTEGRATED SURVIVABILITY ANALYSIS

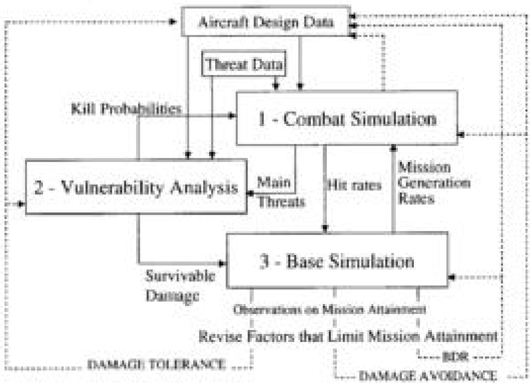
This section describes a BAe-proposed Integrated Survivability Analysis Process, which is a minor enhancement of BAe's current Operational Analysis process. This will enable the better consideration of all the ALFAS elements and, in particular, the balancing of the components of survivability using an approach that:

- evaluates the combat effectiveness of aircraft concepts using improved combat simulation techniques.
- maximises the sustained force effectiveness using parametric studies to identify the design features necessary to minimise attrition and maximise mission generation.
- supports design in minimising aircraft vulnerability in accordance with DEF STAN 00-970 Ch.112 requirements.
- carries out survivability analyses to develop BDR requirements in accordance with DEF STAN 00-60 Task 303.2.11 (Survivability Trade-offs) and MIL STD 1388 Task 303.2.11 (Survivability Trade-off) requirements.
- actions trade-off studies (including those of EW/LO *vs.* damage tolerance) and focuses survivability-based research resources to gain maximum benefit.

The power of this approach is that each potential enhancement feature can be evaluated in postulated wartime environments, thus effectively yielding a 'real' picture of losses and mission generation to replace the theoretical one shown in Figure 3. This proactive design approach is much improved on the reactive one mentioned in Section 2.1. The aircraft is designed in theory and high quality simulated wars are 'fought', then lessons can be learned and the design appropriately updated, leading finally to engineering the solution.

[6] ***Pk*** is the probability of kill of a weapon system when fired at the aircraft. ***Pk reduction*** is a quantified reduction in Pk when a particular countermeasure, tactic, manoeuvre or combination thereof is used by the targeted aircraft against the threat weapon system, pre- and/or post-weapon launch. ***Ps*** is the probability of surviving this simple engagement and is (1-Pk).

Figure 8 - INTEGRATED SURVIVABILITY ANALYSIS



5.2.1 COMBAT SIMULATION

Combat Simulation is intended to prove weapons system concepts. This analysis can be used in two ways, to explore and formulate future requirements or to actually assess the capability of an existing product. This is the first phase in survivability analysis where the baseline design is established and possible enhancements evaluated. The appropriate survivability enhancement measures depend on the aircraft's intended mission, and the three components need to be tuned to provide balanced Survivability for a specific role. The analysis framework examines combat operations in several ways. Detailed system operating models are assembled in an engagement model, which examines the offensive and defensive capability of the aircraft, air and surface threat systems, and assesses the performance of the basic design. The modelling measures mission effectiveness in terms of the required fleet size and this gives an initial comparison of different aircraft types. The effect of damage avoidance features is the primary issue in individual engagement modelling and these take account of the probability of a successful missile lock-on and launch from a hostile aircraft or ground weapon system. The analysis results also support the optimisation of the aircraft design because the aircraft model uses a series of system representations covering aircraft performance factors, aircraft signatures, weapon system function, defensive aids, sensors and human factors and each to feature can be varied and evaluated. A specific type mission is examined for the particular aircraft type being considered. The mission can be selected from the following range of generic missions applicable to 'fixed wing' aircraft.

- Close Air Support and Ground Attack
- Air Superiority and Air Defence
- Strike, Interdiction and Land Reconnaissance
- Supply and Transport
- Tanker, Airborne Early Warning and Maritime Patrol

The mission indicates the relevant operating scenario, the performance requirements and the typical threats involved which in turn enables an evaluation of the combat situation. This combat simulation would evaluate the relevant tactics and define realistic threat encounter situations for consideration in the vulnerability analysis, and indicate damage and loss rates for inclusion in the scenario evaluation. The scope of modelling is gradually widened building from 'one on one' combat, through multi-aircraft missions, into a campaign analysis which develops the conduct of the war through its various stages reflecting variations in the type of mission and intensity of the conflict. The real benefits of BDT and BDR start to appear in the cumulative picture and so need to be assessed in detail at the campaign level, thus focusing on the overall benefits. At this stage the analysis is acting to integrate systems within the aircraft and the systems of systems outside the aircraft producing a realistic and thus sophisticated overall picture of the war. The generic process is shown in Figure 8, and this shows how the resulting survivability elements' effectiveness can be evaluated and revised to develop the combat simulation.

Whilst maximising BDA is always preferred, cumulative damage and loss effects over a sustained period can highlight that even small damage rates ultimately impact on operations. In peacekeeping operations for example, where zero attrition is the aim, even a low loss rate would be politically unacceptable, so vulnerability requires attention also.

5.2.2 VULNERABILITY ANALYSIS

The vulnerability analysis uses the main threats and attack situations, as defined in the combat simulations, and simulates the terminal stage of the attack in more detail. The analysis has three prime objectives, to:

- evaluate the inherent vulnerability of the design and combat support evaluations.

- identify possible design enhancements and provide the associated penalties for trade-off studies.
- define survivable damage in support of BDR planning.

During the conceptual phase the aircraft and threats can be modelled in simple generic terms, which address the major configuration and technological aspects. During the development phase more detailed evaluations are carried out to examine questions of redundancy, separation and the precise hardness of the structure, systems and components. The vulnerability analysis has several stages:

Threat Definition: The prime threats are described in the technical terms that quantify their terminal attack geometry, fusing and the damage potential of their warheads. The blast, fire raising, fragmentation and penetration capability of the threats, against various generic parts of aircraft, are quantified from intelligence data, firing trials and engineering assessments. A range of encounters are normally defined to adequately account for the practical variability of damage in the real world situation.

Aircraft Definition: A computerised model of the aircraft 'target' is created. This has to accurately represent the physical layout and function of the aircraft and the behaviour of its parts when impacted. The content of the aircraft model depends upon the relevant kill category, which in turn depends upon the question being asked of the specialist. There are three basic questions - after the hit will the aircraft be capable of continued controlled flight, completing its mission, or being turned around for the next mission? A major analysis would then be structured to address each question in turn and it can be seen that the third question leads into the analysis of BDR. The results can be used to discern between an instant kill (which would lose aircraft and crew) and a longer term kill - to define for example whether the aircraft would return to base or not. Again the design can be update to produce a harder aircraft if this improves operations overall.

Aircraft Analysis: The aircraft computer model includes a representation of the structure and systems that make up the Air Vehicle. A simulated attack on this aircraft representation quantifies the effect of fragment penetration across the systems. The resulting damage and kill probabilities can be presented at Air Vehicle level to provide an aircraft kill probability or at the individual system level which shows which systems are at most risk. The air vehicle results support Operational Analysis and Base Simulation studies where the number of lost and surviving aircraft is important. The detailed system levels results support design enhancements where individual systems can be protected to reduce the numbers of aircraft lost. The basic data from the vulnerability analysis is stored for conversion into survival probabilities, which are used in the Base Simulation, and wartime spares predictions. A detailed survivable damage definition can be provided to model damage in the Base Simulation. This is also used to feed into the support organisation to develop actual repairs.

5.2.3 BASE SIMULATION

A Base Simulation exercise models the precise operation of an airbase and covers the normal maintenance and supply operations, the reliability of all functions and the allocation of resources. This is normally done for peacetime operations to help minimise LCC. This process can be used in an alternative way to investigate the operation of a wing of aircraft in a wartime environment. The scenario used in the combat simulations is matched in the Base Simulation for consistency. The damage and loss rates from the combat model and the vulnerability analysis results in terms of a survivable damage definition provide and an estimation of the relative rate of damage and the type of damage to be repaired. A re-combination of the vulnerability results can also be used to generate a profile of wartime spares requirements and that can be used in the Base Simulation to evaluate the necessary spares provisioning. The modelling here creates a preview of the real operational curve rather than the theoretical shown in Figure 3. MIL STD 1388 calls for this type of analysis to develop BDR requirements. The results of the base simulation quantify the likely aircraft turn round times and thus the potential mission generation rates in a conflict. This feeds back up into the combat simulation to reflect aircraft availability. Thus the simulation of the overall campaign reflects both realistic loss rates and realistic mission generation rates. This can be used for trade-offs aimed at maximising mission generation through the tuning of specific maintenance and provisioning philosophies. The results can be presented in a variety of forms to illustrate the effect of maintenance and operational parameters. The effects of Battle Damage can then be shown in terms of attrition rates, the number of aircraft under repair and the resulting number of missions generated. Spares, materials, manpower and workshop/repair kits can also be defined.

In a further innovation this modelling could be applied to the airbase itself and look at the damage and repair requirements for the key airbase functions. Operation of aircraft from an aircraft carrier for example could be critical if aircraft damage and loss rates rise. This type of analysis could ensure that the limited resources are optimised for maximum effectiveness - a crucial aspect when operating out of area in potentially urgent operational conditions.

6 COST CONTROL (WHAT HAS AND WILL BE DONE)

No aircraft is more expensive than one lost in combat. Survivability thus is invaluable in ensuring that, when in the midst of a conflict, when defensive or offensive air power is really needed, it will be there - ready for use. The ultimate value of the product lies in its operational purpose and there is little chance of replacing a lost aircraft in the middle of a conflict, possibly well after the production line has closed. It is fairly ironic therefore that the majority of aircraft cost controls are actually aimed at the peacetime costs. Project costs are probably the most important factor in the success of a new project – it must be affordable to gain entry to the marketplace in the first place. Affordability is all-important and costs have to be competitive to actually win the business in the international arena. Cost predictions must also be reliable since a failure to achieve the predicted cost can result in cancellation or potentially result in some form of penalty such as liquidated damages which can result in commercial difficulties for Industry.

The level of technology involved in survivability enhancement is likely to have a major impact on the cost of the project. The two R&T drivers, the ALFAS elements *Affordability* and *Survivability* are clearly inter-dependent and quite often contradictory. BAe and DERA R&T agencies not only initiate, develop and mature the necessary new technologies; they also assess the potential cost, and aim to control the cost of the technology, and related materials and processes. These processes include design and analysis processes, design tools and data storage, manipulation and access. In the context of Survivability there is the drive to increase product capability using expensive technologies as outlined above. The cost challenges are to:

- accurately define the potential cost of the necessary technologies to initially estimate the product cost.
- develop and maintain reliable cost controls.
- ensure that all costs: development, production, operational, wartime and disposal are assessed and controlled.

A trade of cost against performance will ensure that the design meets the functional and commercial requirements of the customer to make it the right product. It is only possible to provide the right product at the right cost by using accurate, comprehensive and reliable cost data.

A further, new element is to understand and control the actual wartime operating costs including the potential wartime attrition, which is directly influenced by survivability.

6.1 COST ESTIMATION METHODS

A traditional way of estimating project costs is to examine past projects' costs and extrapolate to the new. This is fairly sensible and hopefully safe since progress up the learning curve would enable Industry to perform the work for less cost than the earlier projects. Bearing in mind the historical 'Cost Plus' culture, where the actual cost was not a primary concern of design, this cost extrapolation process could well result in higher than necessary costs. Cost inaccuracies and errors of the past may effectively be repeated since they were not then under rigorous control. One approach, using a Parametric Cost Forecasts method, is based on the main cost-related parameters which identify the changes in these from one project to another. Changes in the main elements will be reflected in changes to the cost. This method is useful in producing relative cost data, but the accuracy of the base cost is still a probable source of error in producing definitive costs. Two methods of cost prediction have been used by BAe:

The 'Bottom Up' approach is a detailed, accurate and reliable systematic engineering analysis of the design and manufacturing processes necessary to produce the product. Its aim is to guide design and manufacturing departments to the optimal cost solution and then, through trade-offs, to control cost. It relies on the use of a broad definition of the design, worked through systematically, and the use of engineering judgement and experience to assemble an overall assessment. A cost estimate would be built up from items such as the aircraft layout, the systems, sensors and technologies used, the anticipated assembly process, typical man-hour requirements, materials and tooling costs. Once the initial cost estimate has been built up it would be a valuable source of accurate cost data. The results would allow further investigations of options and trade-offs. The use of cost assessment tools, standardisation of assumptions and cost engineering relationships (the main parameters), may enable respectable cost tolerances of around ±15% to be achieved. This approach requires up front detailed design information, which is very reliable in obtaining the required results. However this method of costing can sometimes be time consuming and relatively slow.

The 'Top Down' approach, on the other hand, is a relatively quick and cheap parametric approach and can be considered to be driven from a management rather than an engineering perspective. It is automated and requires no deep engineering knowledge. It cannot support an extremely detailed breakdown analysis and so further decomposition of data is difficult and specific forms of trade-off could be difficult.

The normal approach used is the latter, using estimating models whose primary aim is to define the order of magnitude of potential costs. In this case the analysis is often done at a high level (with low detail), using the key parameters relating to the cost being examined.

The estimation of Operational and Support Costs for example, which are a major element of LCC, would use a whole range of inputs. Reliability and Maintainability predictions, defect rates, maintenance man hours/flying hour, operational use, peacetime attrition, labour costs, spares costs, administrative and operational backing, fuel consumption and station overheads as some of the main parameters used.

6.2 LIFE CYCLE COSTS -WAR AND PEACE

LCC are used in an attempt to discover the true cost of ownership of a weapon system. They are more representative of this cost than just purchase cost, since they also include operating and disposal costs. Individual LCC constituents are many, but the important ones from the Customer's perspective are the purchase price and the cost of through-life support. The purchase price is reliant on design and production costs. The operating cost is normally based on (say) twenty-five years of peacetime flying and the maintenance support. Since costs are often scaled from existing projects, as noted above, operating costs are often scaled from earlier maintenance philosophies and a novel concept could be difficult to predict accurately. In addition to the traditional peacetime costs there is another major element, which Industry does not usually become directly involved in, and that is the war fighting costs. This is probably the most important element in the sense that military aircraft are produced to fight wars and full operation during war should be an *economically viable activity*. Linking these costs to survivability introduces the ability to measure and to trade technical performance *vs.* cost, including that of wartime operations. This then adds a new element to the cost equation – *combat costs*, in which per-aircraft and fleet survivability is arguably one of the two dominant factors, the other being ordnance costs.

Actual war fighting costs, including attrition costs, can be based on the data that is developed in the survivability analysis discussed earlier. As well as developing and proving the right type of weapon for the mission, such methods of survivability analysis can enable evaluation of mission cost *vs.* weapon options. This is important as the Customer must be able to afford to use these weapons in anger if and when reuqired. By adopting a holistic approach to costs and survivability, where war fighting costs are included, the Customer can be aware of the true LCC of the aircraft. The Customer will consequently gain the ability to win conflicts cost effectively and without incurring massive war debts. To enable this enhancement in LCC control, aircraft design priority has to change so that wartime functionality and operating costs are the priority (survivability analysis covers both), followed by peacetime function and costs. This is a major change in emphasis and will ensure ultimately that increased survivability and efficient cost control delivery of what is required by the Customer - adequate capability at the right price.

6.3 COEIA, JOINT WORKING AND THE 'BENCHMARK' APPROACH

The Combined Operational Effectiveness and Investment Appraisal (COEIA) process has been used by MoD U.K. in recent times to determine the 'best' solution to a given military requirement. For a given requirement, *e.g.* the functionality and performance traditionally performed by a given aircraft type, the DERA will consider a range of options and advise MoD a short list for further examination. Once examined, an Invitation To Tender is issued and bidders are required, as part of their proposal, to provide MoD/DERA with a full set of technical and LCC data for insertion into the MoD COEIA database. The results of the COEIA assessment of the bidder-provided information on their proposed solution to the MoD's requirement are then used to rank the various solutions on offer, which often include some solutions studied by DERA/MoD internally. The COEIA methodology is seen as a key aspect of U.K. MoD's decision making process, and is thought likely to be used more stringently for the foreseeable future as the need for affordability remains.

The Customer-Supplier relationship is at the centre of any successful project and these relationships are maturing through the collaboration and mutual understanding that the COEIA type of activity necessitates. A full and effective response to this type of requirement is bringing about something of a change in the way the Military-Industry partnership operates. In the context of the COEIA it is essential that Industry teams act efficiently as a whole and, since this activity is effectively a competitive bid process, it is essential to submit the best response to achieve success.

The changed priorities described earlier mandate a proactive approach, rather than the reactive way of working of earlier times. BAe, for example, has embraced the need for closer military/industrial partnership to ensure the best mutual understanding of requirements, issues and problems. By working together to clearly identify, understand and categorise technical and commercial drivers, the solutions with optimal features and balance can be arrived at. BAe has enshrined this proactive approach in its set of five central Business Values: Customers (the highest priority, with emphasis on working well together and understanding each other's priorities and challenges), People, Partnerships, Performance, and Innovation and Technology. Working closer together with Customers, Partners, Collaborators and Suppliers helps develop a common understanding of the design challenges and strengths and weaknesses of the partners. The use of Earned Value Management and Cost Benefit Analysis techniques also enables improved cost control by linking the cost of any activity to the output of that activity.

6.4 SURVIVABILITY *vs.* COST ASSESSMENT - AN EW PERSPECTIVE

In 1989/90 a major study, *'Low Cost Self Protection Fit for NATO Tactical Aircraft'* [8], was conducted by NATO AGARD (now Research and Technology Organisation - RTO). Aircraft operations in a number of Cold War regional scenarios were considered, threats postulated and their individual lethality estimated. A number of viable EW fits (suites) were then constructed and their respective and relative performance modelled and/or estimated against the threats in those scenarios. A total of 30 threat/countermeasure pairs were considered. It was noted that although the derivation of Pk reduction "*was essentially subjective, the forum of international expertise given the opportunity to explore this subject in depth is probably unique and probably represents the most consistent comparative evaluation of ECM effectiveness available at this time.*" This resulted in an effectiveness ranking, with the minimum fit thought viable - RWR and Chaff/Flare - obviously the lowest (other than having no EW suite). Cost estimates were made for each of the fits considered and graphs of effectiveness *vs.* cost were presented. The study at [8] also examined the situation for tactical aircraft with and without support jamming, whose benefits are well known *cf.* [8] and as seen recently in Kosovo and Serbia with the widescale use of the EA-6B 'Prowler' aircraft.

In 1996 Pywell and Green of BAe conducted further survivability enhancement investigations [9], starting with (*inter alia*) material in [8]. They primarily addressed the issue of how to increase aircraft survivability by better Self-Protection (RF) Jamming capability. During the investigations, various aspects of [8] were reviewed, with due consideration also given to other data available to BAe and previous work by K. Smith *et al.* of BAe's Operational Analysis Department.

The key revisions resulting from the study were:

- The original scenarios were made more generic,
- The threats and their Pk values were revised, and
- Pk reduction values assigned to countermeasures and countermeasure techniques were also revised.

Ref. [8] gave six generic EW fits from those fitted to the many NATO fixed wing aircraft that study group examined. To this was added a further nine, resulting from their assessment of threats and countermeasures in the scenarios considered. The later investigations in [9] resulted in modifications to a number of these fifteen fits, the merging of others and the addition of two new fits, which were considered to be the most effective (and, alas, the most expensive).

The revised fits, fourteen in total, ranged from the minimum viable RWR plus Chaff/Flare to arguably the most potent self defence suite, comprising ESM, Flare/Chaff, RF Expendables, MWS, On-Board RF ECM with Digital RF Memory (DRFM) technology in concert with Towed RF Decoys (also with DRFM technology), and DIRCM. It should be noted that this wholesome capability is not achievable on tactical aircraft at this time with currently available EW equipments. The earlier costs were also reviewed, although it still remains difficult to obtain realistic cost estimates for individual elements of an aircraft DAS or to extract them from system quotations.

An initial version of Figure 9, the summary graph from the study at [9], was developed in response to a MoD query concerning costs *vs.* EW capability. This graph showed a 'best estimate' at that time of the dependency of EW system content/complexity *vs.* delta increase in effectiveness *vs.* approximate average purchase cost (not LCC). Figure 9 has been sanitised from [9] for this Unclassified paper - primarily by omission of the AGARD data from [8] and of all the specific EW fit identifiers. It thus shows the BAe view at that time. The cost axis has been simply escalated to account for inflation since the time of [9].

Figure 9 is not intended to represent a definitive relationship between EW system elements and Survivability, rather to show high quality trends. It is considered to be the best picture available at this time and is thought to be equally applicable to most military aircraft types. It does, however, allow a first order approximate equation to be developed linking increases in survivability with delta cost, for input into the proposed EW *vs.* damage tolerance trade-off studies mentioned earlier. It is considered that most of the fits in the Figure fulfil, to a large degree, the recommendation in [8] that self protection fits should be as threat independent as possible.

Notes on Figure 9:

1. Laser Warner (LW), which now appears in most Customers' requirements, was excluded from [8] and [9] as the original scenarios of the former did not contain laser guided or augmented threat weapon systems (there were few at that time). A further reason was that, as countermeasures for tactical aircraft had yet to be developed, LW inclusion was thought to only change the overall effectiveness by a small amount. The proliferation of such weapon systems and laser-based updates to existing systems seen in the last few years suggests the time has come for a review of the impact of LW inclusion on the EW fits in Figure 9.

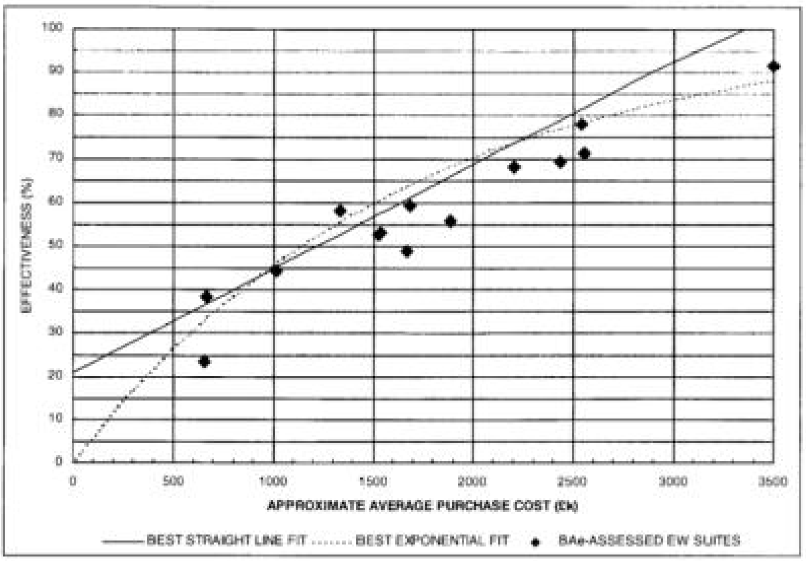


Figure 9: EW Suite Content *vs.* Cost *vs.* delta increase in Effectiveness

2. At the time of [9] no Pk reduction figures were available for DIRCM and thus a maximum effectiveness improvement of 10% was thought applicable. There remains a need for ratified Pk reduction values for DIRCM *vs.* various threat systems to be determined, to enable a realistic estimate of effectiveness improvement and thus the credible assessment of the cost *vs.* survivability benefits of this relatively new countermeasure type.
3. Some of the more esoteric RF ECM techniques were assessed in [8] as too costly. This was reiterated in [9], which recommended their examination at some future point when either the threat scenarios warranted it or when cost-effective technological or other improvements occurred. One is currently being studied by BAe.

Three possible equations were determined using best fit techniques: a curve, a straight line without using the zero cost/effectiveness point, and an exponential curve using that point.

$$E = -1.68E\text{-}6*C^2 + 0.0296*C + 16.7 \quad ...(1)$$

$$E = 0.0239*C + 20.8 \quad ...(2)$$

$$E = -5.07E\text{-}6*C^2 + 0.0425*C + 5.85 \quad ...(3)$$

where E = percentage effectiveness and C = cost in £k.

The relevance of the zero effectiveness/cost data point is again a function of the definition of the term 'effectiveness'. The [8] assessments, and hence those reported herein, were of Pk reductions for a given EW fit against the threats, relative to the 'no EW equipment' case. Since no weapons have a Pk of 1.0 (*i.e.* fire one missile = kill one aircraft, every time), it is arguable that even with no EW equipment fitted, the aircraft will not necessarily be 'killed' when fired upon and hence a non-zero value would be applicable if the y-axis were absolute effectiveness. However, since it is actually a relative scale, showing ***delta increase*** in effectiveness, further inspection suggests an exponential fit would to be the most appropriate. A suitable exponential fit is given in equation (4) and is shown with equation (2) on Figure 9. It has a zero/zero start point and asymptotically approaches 100%. This is intuitively correct - a perfect EW suite would cost infinite money.

$$E = 100*(1-e^{-C/1650}) \quad ...(4)$$

Further investigation of the data on Figure 9, their underlying Pk reduction dependencies, and the best fit equations are required to arrive at a multi-variate final equation, which would better show the contributions of the individual elements of each EW fit component. This final equation would have a number of obvious dependencies, which require further investigation and quantification. These may be briefly listed as:

1. RF and electro-optic environment for given missions and scenarios.
2. Level of complexity of EW elements fitted, particularly the equipment for sensing the threat and that for countering it. (The relative capabilities of RWR and ESM is a good example.) Definition of threat weapon systems and their susceptibilities.

3. LCC rather than just purchase costs, *i.e.* including maintenance, expendables and consumables costs.
4. Formation aspects, *e.g.* a) does every aircraft need a comprehensive EW suite? and b) what is the impact of SOJ/ESJ on formation survivability and formation EW system costs?

Methods and tools are required for evaluating EW elements/fits and the resultant impact on the locus of the exponential line and points on Figure 9. It is envisaged these will:

- Enable comparative assessment of performance, cost and survivability improvements between EW equipments, initially between those of a particular type and eventually between entire EW suites.
- Assist in the identification of those technology advancements which are most likely to yield cost reductions and/or performance increases with zero cost increase.
- Help maintain tight focus of the U.K.'s R&T resources on those areas most likely to benefit the Military Customer.

7 CONCLUSIONS AND THE WAY AHEAD

The Value of Survivability is best shown by looking back at the 'War' as shown in Figure 2 and comparing it with the version shown in Figure 5. The first represents the old 'Re-active Situation' and latter the new 'Pro-active Situation'. The air force adopting the new approach will have a superior capability to one operating in the old way. The benefit from incorporating Survivability is winning the war.

The Enigma is Complex and no single answer exists. For clarity it is reiterated here: ***'How can aircraft survivability be increased, to ensure improved war-time availability, whilst simultaneously meeting the increasingly strict affordability levels dictated by Defence Ministries and mandated by competition for military business world-wide?'***

1. For existing aircraft, there

- appears no way of increasing survivability at reduced cost on a *per-aircraft basis*,[7] especially with the application of the 'near zero' attrition philosophy of modern multi-nation operations. Either the aircraft is provided with enhanced EW equipment, and/or better on- and off-board situation awareness is provided, and/or it is hardened against physical damage – all of which increase cost.
- is some potential for fleet survivability enhancement with decreased *Life Cycle Costs* through application of an innovative Integrated Survivability Analysis Process, which takes into account all aspects (including aircraft LO/EW and vulnerability, and Battle Damage Repair capabilities and main/forward base survivability).

2. For new aircraft there is potential for increased survivability (a real chance for 'near zero' attrition) and reduced cost, compared to previous aircraft, by the rigorous application of the above Analysis Process. It is suggested that the benefits would be highest for a balanced mix of BDA, BDT and BDR improvements, and that cost benefits would be greatest when considering fleet Life Cycle Costs, *including* war costs.

3. For existing and new aircraft the three keys to resolving the enigma appear to be:

- Conduct integrated survivability analyses as described herein.
- The Military, the Defence Procurement Agencies, their Technical Advisors and Industry must work ever closer and ever earlier together to ensure that requirements, designs and implementations are sound, feasible, survivable and affordable.
- Decrease aircraft vulnerability - make them capable of repair and return to the fray - don't lose them.

4. Military-Industry collaboration is here: there are a number of examples of this collaboration, of which the Future Offensive Air System (FOAS) Integrated Project Team and the DERA-BAe Strategic Alliance are notable examples, whose target is maximising benefits to the Air Force Customer and Industry alike:

- BAe, as a world-class systems integrator and military aircraft supplier, has developed tools and techniques for systems design and survivability modelling, development and assurance. BAe's goal is to assure improved survivability levels commensurate with mission effectiveness requirements and acceptable cost of ownership.
- The DERA, as the U.K. MoD's technical advisors, is equally driven by the above requirements and has been working ever more closely with Industry and other international/NATO research agencies to ensure that U.K. armed forces get the best technology and products at the best prices, consistent with meeting military requirements.

The Way Ahead comprises consideration of these proposed (but unprioritised) topics:

- As most aircraft losses occur when the aircraft finally goes in harm's way (rather than during threat avoidance and evasion) there is a need for better understanding of operational, performance and cost trade-offs between enhanced EW suites, provision of support jamming and decreased aircraft vulnerability.
- Enhance EW fits and provide appropriate support jamming for all raid packages.

[7] Excluding increasing *Weapon System* (rather than aircraft) survivability by the use of stand-off weapons.

- Think, in future, of a single platform baseline survivability enhanced by co-operative operation.
- Investigate a true System of Systems approach – improve interoperability, especially for multi-nation operations.
- Investigate cost issues, especially the impact of the inclusion of war costs in LCC predictions. Inclusion of all costs in the analysis could yield alternative and possibly more cost-effective weapon system solutions to military problems.
- Watch out for the results of the NATO SAS-11 '*Requirements and Options for Future NATO EW Capabilities*' Study (currently in the reporting phase) – it addresses many of the Damage Avoidance issues raised in this paper.

8 ACKNOWLEDGEMENTS

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Enhanced Survivability Through Improved Emitter Location Techniques

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1 Introduction

Swift and unambiguous identification of hostile weapon system type and location is fundamental to mission success and would significantly enhance platform survivability in a hostile environment. BAe has undertaken a study, based on a fighter-sized aircraft, to identify technology and techniques which will reduce the error bounds associated with emitter location. Several strategies have been investigated with the intent to implement the recommendations in a variety of time frames ranging from the short term, 2001 to longer-term implementation in 2005 and beyond.

This paper addresses some of the aspects considered in the study to establish improvements in the EW system of a small, fighter-sized aircraft. The particular airframe considered in the study is an in-service design that is currently equipped with a relatively simple Radar Warning Receiver. The findings of the study so far are considered relevant to the generic case of enabling high grade Emitter Location functionality, irrespective of the air vehicle size but the establishing of a better baseline using aircraft flying in formation has been considered.

During the course of the study it has become apparent that, whereas an extension of the mission profile to include a pseudo-reconnaissance capability might be attractive for some users, a particular concern, however, would be the impact of introducing such a system into the pilot workload and the method by which information is presented.

2 Description of options

The options for the study break down into a relatively small set of possibilities which are constrained by the limits of the airframe, available technology and affordability. The latter has been given little attention to date in this feasibility study, but will be addressed in a subsequent phase. The prime driver is currently perceived as being the availability of technology to establish feasibility in a relatively short time frame.

Paper presented at the RTO SCI Symposium on "Flight in a Hostile Environment", held in Solomons Island, Maryland, United States, 19-21 October 1999, and published in RTO MP-47.

One area currently unresolved is the balance which may be struck between near real-time processing and post-mission data reduction. The problem may be eased to some extent by the current availability of large storage capacities within relatively small physical packages. The objective of improving survivability during a mission argues for near real-time processing for some threat system intercepts, whereas post-mission processing would allow a significantly more powerful array of techniques to be applied to the intercept data.

The following paragraphs set out the main configurations considered.

2.1 Independent Aircraft

2.1.1 Fusion of data derived from existing fit

This approach offers a relatively low-cost solution to the question of improved emitter location. The aim would be to retain the antenna and RF systems and simply replace the computational components of the existing on-board systems. The break point would probably be at the A-to-D conversion stage where modern processing components would offer significant benefits without requiring major airframe changes.

The principal concern relates to the ability of the current sensor fit to provide sufficient data of an acceptable precision. In particular, the adequacy of other parts of the current fit is problematic since, for example, any such process would involve the placement of additional demands on the navigation system.

2.1.2 Enhanced Sensors on the airframe

The foregoing indicates that there is likelihood of a need to improve both the EW sensors and the navigation system. These will inevitably entail some airframe modifications and will therefore be a relatively expensive option when compared with the use of existing sensors. However this approach offers some possibilities for improvement in the performance of the EW antenna systems, particularly in terms of the operating bandwidth. It should also be recognised that whilst some improvement in basic antenna coverage might be conceptually possible, a significant change in the siting of antennas was considered to be a very unlikely prospect.

2.1.3 Use of pod

The use of a pod-mounted system offers a number of possible advantages of which the most important is probably the opportunity for development off the airframe and the consequent possibility of uses beyond the initial target platform. A very important consequence of the use of a pod is the possibility of making significant changes in the antenna sites and of potentially improving the overall system performance.

An alternative form of pod-mounted system was also considered in which sensors on the pod were combined with those situated on the airframe in order to offer some level of enhanced performance.

The survivability enhancement possibilities and promise offered by the use of a pod has the unfortunate down side, from a mission effectiveness standpoint, of using valuable weapon carriage points.

2.2 Co-operating aircraft

The possibility of co-operation between two or more aircraft being to establish an extended baseline has been analysed. This offers improved emitter location performance for a number of systems approaches. The key questions which the element of co-operation introduces are in the areas of the impact on pilot workload and data transmission. The latter includes aspects such as bandwidth, vulnerability to exploitation and jamming as well as the operating ranges. The impact on the pilot workload was examined with respect to single aircraft operation, aircraft operating in formation and those aspects associated with using a pod. The conclusions are that onboard processing was necessary in that, when observations are made, the pilot may have to concentrate on more important operational issues. The mechanism to alert the pilot will be addressed in subsequent phases in consultation with the appropriate staff.

2.2.1 Master fitted with pod

This system configuration is conceptually the simplest but offers the poorest performance improvement as well as posing a potentially unacceptable pilot loading. A group of aircraft, of which only one is fitted with an improved pod-mounted system, are required to co-operate. This will, inevitably, require significant amount of pilot involvement to overcome the shortfalls of existing systems, in particular there will be a need for the communication of the output from the on-board systems and inform aircraft in the formation to take specific stations.

2.2.2 Master Specific to Task

This approach shows little improvement over the preceding one, with no significant improvement in the onboard installations of all the co-operating aircraft the benefits are small. The improvement over the previous configuration is that, potentially, a dedicated aircraft might have significantly enhanced processing capability compared to a system that is constrained to a pod.

2.2.3 Close formation all with pods

The provision of pods on the whole of the group of co-operating aircraft offers significant improvements over the previous configurations. A key factor here is the possibility of providing dedicated communications as part of the pod installation rather than trying to use an existing communications fit. The use of pods for the system will still impose some constraints in areas such as power handling and the interface with the parent airframe. However, the main, significant drawback with the use of pods is the reduction in the number of weapons stores which could be carried on the pylons.

2.2.4 Close Formation, Master Specific to Task, remainder with pods

This configuration is only likely to offer benefits to the extent that a dedicated master aircraft might be able to bring more processing to bear in near real-time than would be possible with a pod-mounted system. The obvious penalty is the need to extensively modify the installation on some airframes and the question of the mix of airframes would then become crucial.

3 Sensor performance

A key element in the assessment of methods of improving the emitter location capability of a system is the quality and accuracy of data gathered by the sensors. A short study has been undertaken to compare the performance of pod-mounted and airframe-mounted sensors.

The modelling performed has used a heavily stylised airframe model, which is illustrated in Figure 1. The figure shows the airframe with twin pods installed out-board on the wings and the arrows indicate the location and look directions of the antennas considered, broadband spirals. The same airframe was also modelled with antennas mounted in typical fuselage sites. The broad conclusions of this study were that the pod-mounted antennas offered significantly better performance than the fuselage-mounted sensors simply because their performance was much less affected by interactions with the empenage and other structure. This is illustrated in Figure 2 and Figure 3 that show the predicted azimuth patterns at a range of elevation angles for pod and fuselage-mounted antennas respectively. It is worth noting that the inclusion of the under-chin air intakes and the canard configuration impose very significant constraints on the choice of antenna sites on the fuselage and the practicability of the site modelled was questioned on these grounds.

During the study consideration was given to the means by which data on emitter location might be extracted from the sensor suite. Three different techniques were considered as candidates: Amplitude comparison, Phase comparison and Time Difference of Arrival.

The applicability of these candidates was found to follow the following outline:

1. Amplitude comparison could be expected to give useful performance on the configuration modelled in Figure 1. Its usefulness for fuselage-mounted sensors was considered to be much reduced because of the difficulty in achieving the required coverage. As an illustration of the possible performance Figure 4 plots the error slope over a 90° sector for this configuration.

2. Phase comparison was found to be a poor candidate for any of the modelled configurations because of the difficulty of ambiguity resolution. A wider baseline produces lower error bounds. To resolve ambiguity it is necessary to position the sensors closer than $\lambda/2$ or, alternatively, to use information that is extracted from third parties.

3. Time difference of arrival was found to be unusable for a single airframe of the size and agility considered in the study. In order to

achieve useful performance it was found necessary to have baseline lengths of the order of several hundred metres. This configuration would be possible for a group of aircraft.

The conclusion of the study, in terms of emitter location, was, therefore, that, for a single airframe, a system based on amplitude comparison was likely to be the most beneficial in the short term. The prospects for the use of more sophisticated approaches, for example, differential Doppler or TDOA will depend on the development of appropriately packaged processing systems suitable for installation in this constrained environment. It was, however, also concluded that for a group of aircraft then the time difference of arrival technique was worthy of very detailed consideration.

4 Description of fusion methods

An extensive set of references is available on this subject and we have identified a number of techniques which may be appropriate for this application. Of particular interest is the class of systems which can be decentralised, (viz. the work by Deaves *et al.* from BAe Sowerby Research Centre). We, in this study, have not been limited by the strict definition of 'decentralised' in which each sensor has an element of the processor and is 'all-informed', but have considered a wide sense application. In this context we have considered distributed processing but with restrictive communications and, in particular, the impact of phases when communications are denied.

The specific algorithms fall into classes roughly characterised by:

- Decentralised Kalman in its space state or information form
- Probabilistic (Bayes)
- Evidential Reasoning (Dempster Shafer)
- Neural Networks.

To some extent the processing architecture will influence the performance but this aspect will be considered in a latter phase of the study. The work we have identified at BAe Sowerby Research Centre has concluded that a Bayesian-based information filter is best employed as a kinematic estimator. In the context of this investigation the implementation is computationally less expensive than the equivalent Kalman and has been reported elsewhere with considerable success. The distributed processing of the sensor elements will necessitate communications between the nodes in an efficient fashion. It is noted that not all the schema reported are intuitively obvious, but some heuristics have been established which will form the basis of further study.

5 Discussion of non-real time assessment

In order to ensure that system performance is kept at optimum levels, it is necessary for the system's on-board reference database to be provided with comprehensive and accurate updates of the latest geolocation information. In addition, technical data for all relevant target emitters compiled from a wide range of sources prior to the commencement of a mission will be necessary. These updates would be the result of analysis on the ground coupled with supporting collateral information from third parties i.e. satellites. The implications of this would be requirements for on-board recording, the timely transmission of sensitive data between operational and support elements and the establishment of the associated logistic tail.

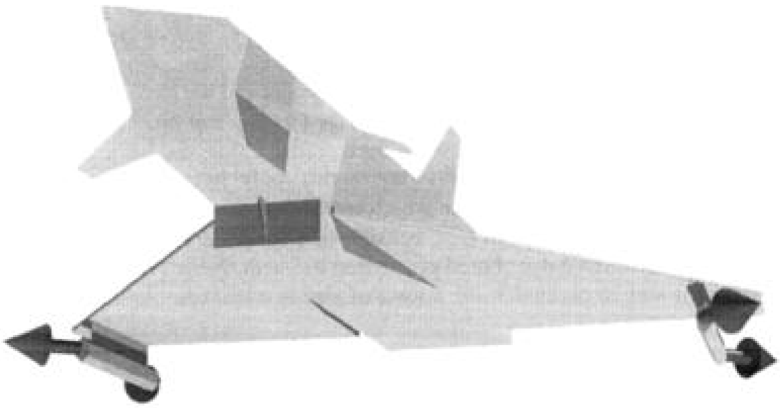


Figure 1: Stylised airframe model showing antenna locations and orientation

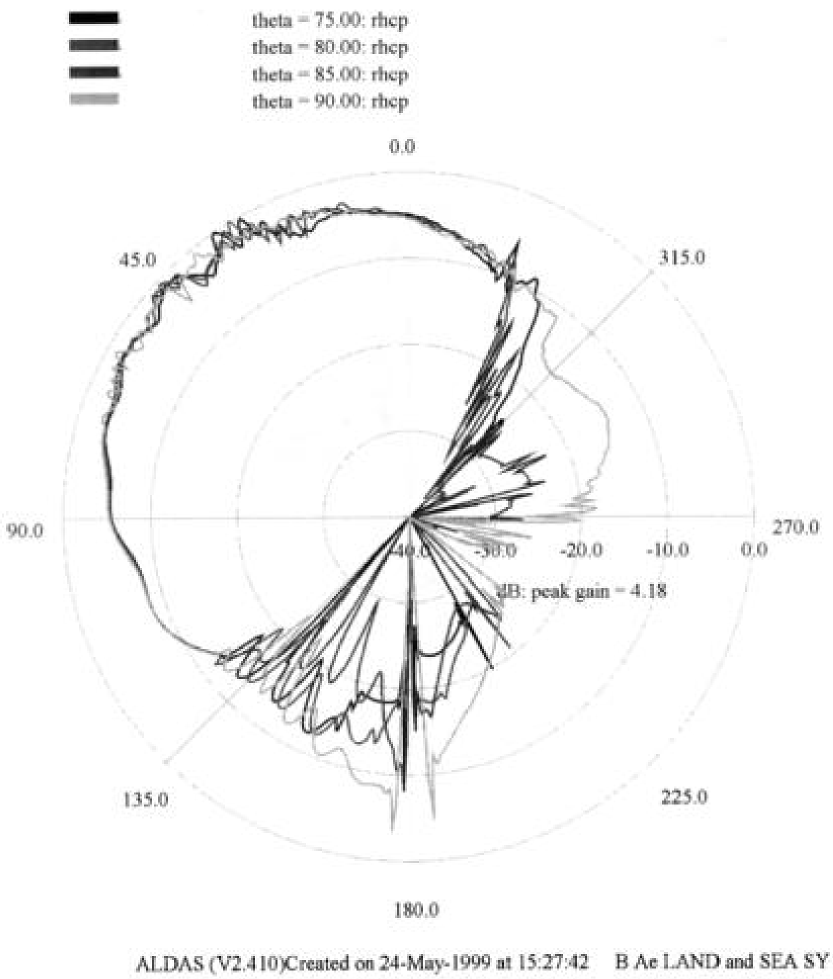


Figure 2: Pod antenna - Predicted azimuth patterns at 0°, 5°, 10° and 15° elevation angles

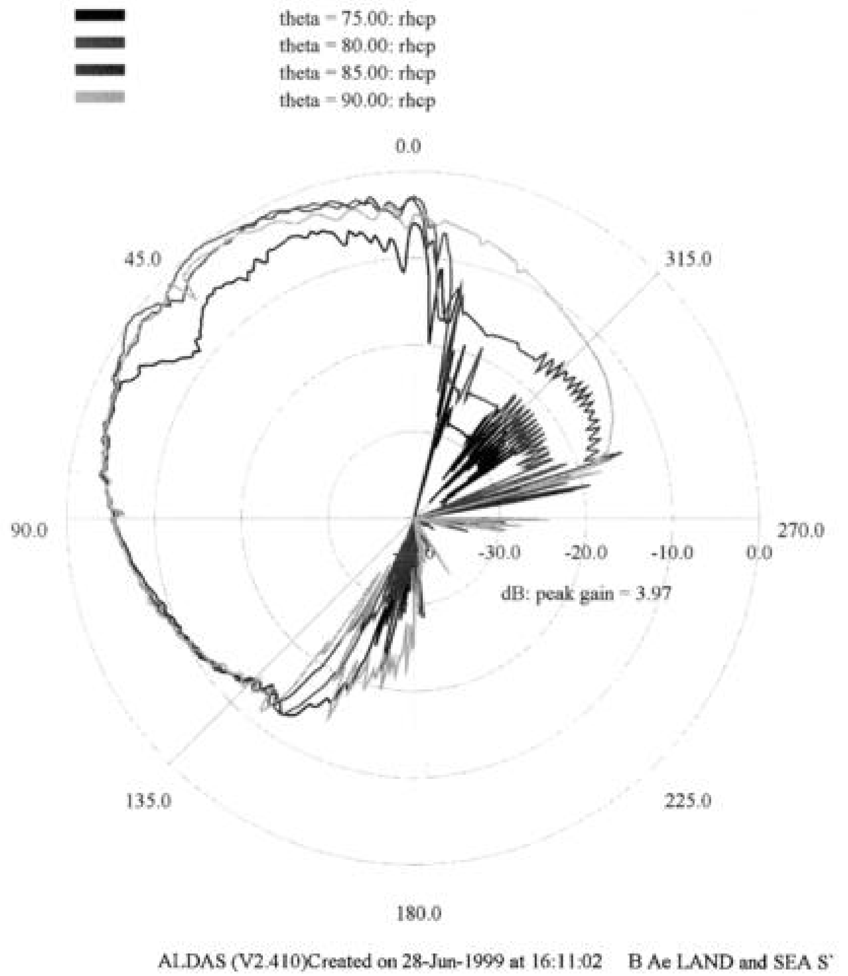


Figure 3: Body-mounted antenna - Predicted azimuth patterns at 0°, 5°, 10° and 15° elevation angles

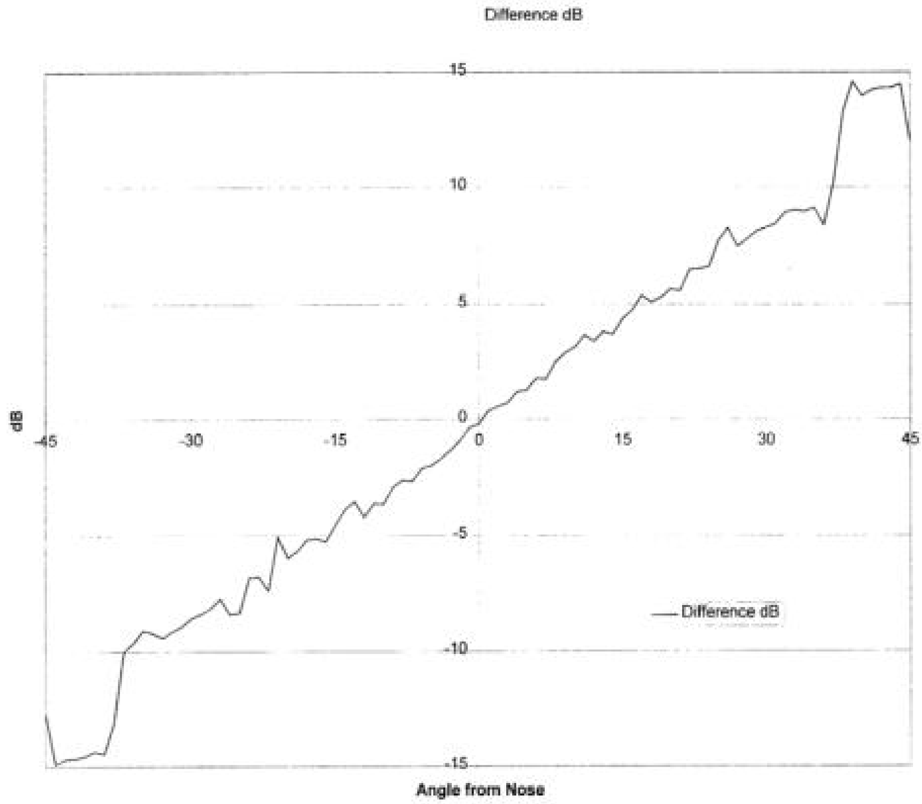


Figure 4: Error slope for amplitude comparison pair of pod-mounted antennas

6 Conclusions

The study revealed that an improvement in emitter location is feasible. The improved capability to precisely detect, identify and locate a threat weapon to enhance its own capability to survive fall into two categories: short and long term.

6.1 *Short Term - 2001*

The first is in the short term where physical constraints imposed by the aircraft structure are overriding and limiting. In this time frame it would appear that the solutions available are confined to:

6.1.1 System Digitisation

The introduction of limited digitised processing into existing systems in order to enhance their overall performance. This may be a feasible option if there is sufficient space available within the systems bay of the airframe house the equipment.

6.1.2 Operational Tactics

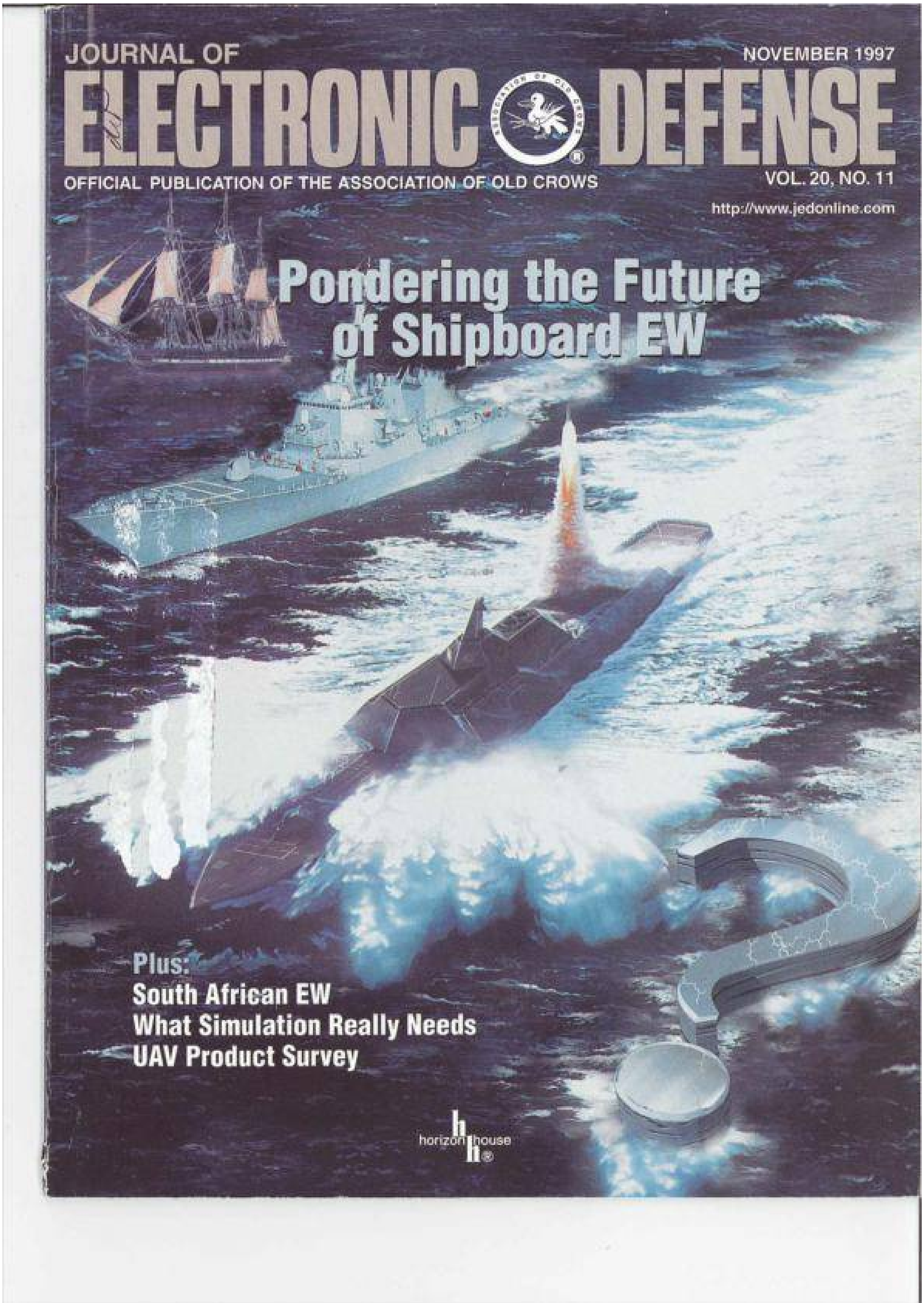
Rationalisation of operational mission tactics to fly co-operating aircraft in formation with a capability of data communications exchange between airframes to improve the quality and accuracy of the threat emitter identification and geo-location capabilities. The major drawback in this solution is the impact on pilot workload to ensure that the required system performance improvements are achieved. A second issue is the impact on the communications channel and the utilisation of currently low bandwidth systems.

6.1.3 Use of a pod

There are a number of significant advantages of supplementing current, onboard EW systems with systems carried in an external pod, mounted on a weapons system pylon. Not the least of these being the amount of flexibility in antenna placement and the capability of incorporating another navigation reference to supplement the main INS on the aircraft to enhance the overall location accuracy. These systems would be capable of either being run in isolation, if they included the latest technology, or in conjunction with existing onboard systems.

6.2 Longer Term – 2005 and beyond

As far as the more strategic, longer term is concerned it is apparent that the electronics industry is well aware of the shortfalls in their systems' performance and the operational need for improvement in data acquisition, processing and geo-location. To this end it is reasonable to assume that future systems will incorporate the technological improvements in terms of digital receivers, digitised processing and fusion of the data. Distributed processing algorithms and architectures are expected to be a fundamental inclusion in future systems.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Chambers such as the US Air Force's Benefield Anechoic Facility, above, can provide a sterile RF environment for more effective EW testing. (US Air Force photo)

Modeling And Simulation — High-Quality and Lower Cost Validation of EW Systems

Mike Pywell

Successful validation of complex electronic warfare (EW) systems prior to combat is a major technical goal of industry, government and military engineers alike. Adequate system performance is crucial to mission effectiveness and crew survivability and is likely to remain so for the foreseeable future. Even as current and future stealth aircraft strive for ever lower multi-spectral signatures, a plateau will soon be reached at which point survivability and mission success will again depend largely on an EW system's capability.

EW systems world-wide have received bad publicity for many years — mainly through appearing to offer substantial technical promises which either have not been, or could not have been, realized. Validation methods, particularly for electronic support measures (ESM)/electronic countermeasures (ECM) systems, concerned the customer and user alike because of poor repeatability and mismatch between laboratory test results and in-service behavior of EW equipment.

Traditional validation methods involving extensive flight trials have the problem of unknown emitters, and can no longer be afforded in the light of shrinking defense budgets. Consequently there is a thrust in the US and Europe to move much of this work to the modeling and ground-test phase, by testing aircraft in an anechoic chamber and a combination of avionic-rig and threat-simulator tests. This work, which includes extensive scenario modeling and the increasing use of EW equipment models, offers promise in not only reducing expensive flight testing, but also overall EW development timescales and costs. This means that the following issues must be addressed. While all are important, this article covers primarily the last two:

- What is the minimum necessary EW suite for aircraft survivability?
- What are the trade-offs affecting EW suite complexity and how are they related?
  - -Radar cross section versus altitude versus ECM capability

-IR signature versus countermeasures capability, e.g., flares
-Use of stand-off/escort versus self-protection jammers
- What is the radar/radio (RF) and electro-optic (EO) environment in which mission effectiveness and survivability are required?
- How to best specify, design and validate installed EW suite performance.

For this faster and less expensive route to validation, better environment and emitter models, more capable and multi-spectral threat simulators are required. Additionally, realistic modeling of EW equipment and powerful analysis capabilities are also needed. Although RF environment and threat simulation tools and equipment have existed for some time, it is only recently that some of the more complex issues of environment modeling, such as terrain masking, have been addressed in any detail. Recent computing power increases now enable some of these tasks to be conducted in real time.

A Royal Air Force Tornado undergoes testing at the British Aerospace EW test facility. (British Aerospace photo)

EW SYSTEMS SPECIFICATION

Detailed knowledge of three items is crucial to the precise specification of EW suites, of whatever complexity:
- The RF/EO threat scenario(s), including geopolitical data to enable inclusion of nonmilitary emitters in the theater of operations,
- High-quality RF/EO emitter parametric data, and
- High-quality operational analysis, covering tactics and the derivation of electronic order of battle.

This information is used to generate time-ordered histories of engagements which form *quantitative* benchmarks of performance for the aircraft and its installed EW suite. Such benchmarks for EW systems include pulse density versus frequency versus time, instantaneous dynamic range requirements versus time, number of simultaneous pulsed and CW emitters versus time, etc.

An ideal EW equipment specification is one where these time histories are included at the outlet so that no ambiguity on performance issues can exist, so that aircraft and EW equipment suppliers can understand what is expected of their products, i.e., what is the definition of "fit for purpose" for that aircraft when performing stated roles and missions. This level of specification, which demands significant modeling capability and effort, is rarely seen in specifications and less often, if ever, included prior to a contract award. It is seen as an area where aircraft and EW equipment manufacturers, in concert with government and air force agencies, can enact major improvements in aircraft EW performance in terms of affordability and reduced development timescales, balanced survivability and operational effectiveness. Use of the modeling tools and techniques described later, during the staff target/requirements phases of projects, is seen as a potential enabler of these major improvements.

EW ENVIRONMENT MODELS

British Aerospace Military Aircraft and Aerostructures (BAe), as an aircraft manufacturer and systems integrator, uses a suite of models and simulators to support the conceptualization, design and hardware development of whole aircraft and their avionics systems. The two most relevant tools are BAe's Airborne Weapon System Engagement Model (AWSEM) and Data Science's EW Evaluation System (EWES). AWSEM enables operational analysts to turn a customer's threat scenario and tactical information into an EOB for EWES input.

Validation of ESM Systems

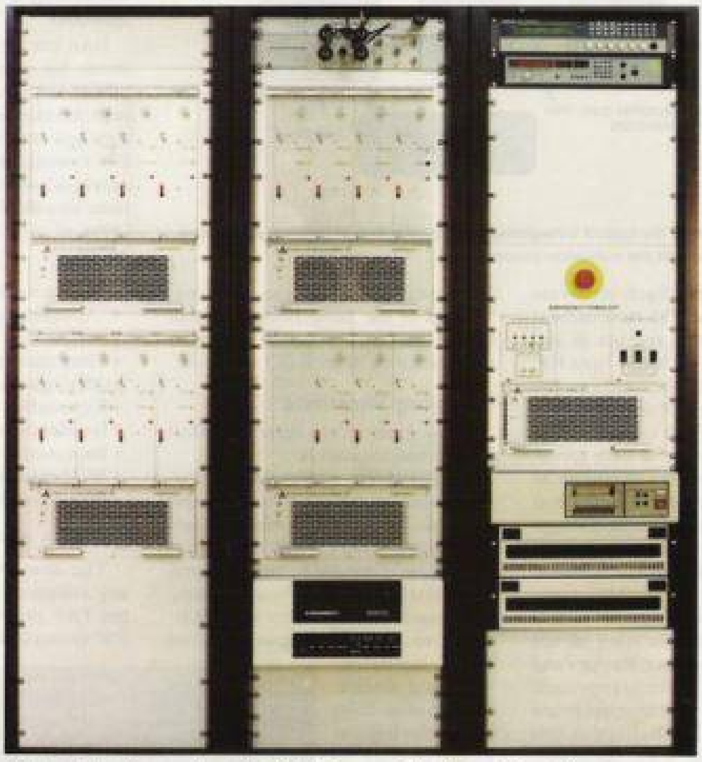
Figure 1 shows the typical arrangement and interaction of receiver model and EW receiver equipment in the validation process, whether at an EW equipment supplier, ground avionic integration rig or aircraft (ground and flight) test stage. This shows how emitter and scenario data is fed to the EWES and RF threat simulator, and how the output of each can be fed into the ESM receiver model and real equipment respectively. The output of the receiver model and real equipment, as time-ordered emitter track files with associated RF parametric and identification data, is correlated off-line with the EWES's Analysis Post-Processor and/or BAe's EW [test] Data Merge, Analysis, Correlation and Statistics package. By predetermining allowable modeling and test error budgets and pass/fail criteria, a suitable regime for the quantitative demonstration of performance to specification can be determined by comparing modeled data with those acquired from rig or aircraft testing of the EW system.

Where full ESM performance cannot be cost-effectively demonstrated via hardware tests, e.g., in the area of maximum pulse densities, the EWES and receiver model are used as the verification tool. This requires that the receiver model is validated. This can be achieved by driving real and modeled receivers with the same emitter scenarios and comparing their outputs. In practice this can be achieved for relatively low-level pulse densities, with subsequent assessment of extrapolation linearity to maximum pulse densities. Typical EWES analysis outputs are shown in **Figure 2.**

Emitter Parametric Data Quality

The performance and effectiveness of EW systems in ensuring survivability and first-time mission success depends on the quality of the emitter data used in the specification and design of, and subsequent programming into modern EW systems. Most new EW equipment is now flight line reprogrammable with the latest emitter data. Such parametrics include primary items such as frequency, pulse width, pulse repetition rate and scan parameters, and more difficult parameters to measure or determine, such as pulse jitter/stagger rate/pattern, frequency agility and modulation on pulse.

Since many RF emitters occupy a fairly small portion of the total spectrum it is hardly surprising that many emitters have broadly similar RF parametrics. This poses difficult tasks for an ESM system — unambiguous emitter identification, often in the presence of many other emitters including the aircraft's own RF sources.



RF threat simulators such as the AMES II are crucial for determining EW system performnce and reducing development time. (Comptek Federal Systems photo)

Parametric data on Red (potentially hostile), Blue (own/friendly) and Gray (neutral/other) emitters is collected through various intelligence gathering methods, including interception of actual transmissions by the threat radar — the ELINT mission. Data is analyzed and collated into an emitter database. These are usually of the highest national and/or NATO security classification. Such data is only released to industry on a project-by-project and strictly need-to-know basis, in relation to specific EW and aircraft contracts. This poses a problem to industry where bid preparation and other precontract work often requires such data to determine the level of EW suite complexity and thus the level of test effort, resources and facilities required — all of which directly impact the bid price. It is thus in the interest of governments and industry alike that suitably sanitized data is available during bid and precontract phases. Although it is possible to construct unclassified emitter databases with a reasonable level of confidence, a better solution to minimize over-specification is believed to be the use of downgraded versions of the national database(s). When using such data in support of EW system specification, design and validation, it is important to maintain adequate configuration control. A thorough method of assessing the impact of adding a new emitter, changed parametrics or behavior of an emitter in a given scenario is required because a change in parametric(s) can result in a significant change to the overall EM environment seen by the aircraft during a given mission.

RF/EO Environment/ Modeling

To date most attention has been paid to RF scenario definition, modeling and T&E facilities. The recognition that the majority of aircraft kills since the Vietnam War have been to IR-guided missiles, combined with the apparently ever-increasing use of lasers as primary or adjunct targeting systems, necessitates the development and use of EO modeling and test capabilities akin to those already well established for the RF bands.

Survivability in future conflicts is likely to be best ensured when aircraft and their EW systems have the previously described scenarios defined in

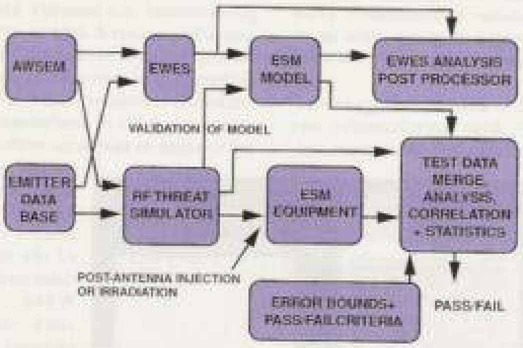


Fig. 1 This figure shows the typical arrangement and interaction of receiver model and EW receiver equipment in the validation process.

multispectral terms. Such scenarios would describe the EM environment that the aircraft must operate in and would include the RF bands from HF, through the established microwave bands, selected parts of the upper millimeter wave band and various IR and UV wavelengths. Should such speculative directed energy weapons as high power microwave, non-nuclear EM pulse and laser dazzle/damage prove viable, then these too would need to be included in the scenario specifications.

These multispectral scenarios will enable precise specification of not only ESM, but also laser warners and IR/UV missile launch/approach warners, and will enable appropriate specification of multispectral test equipment for T&E work, particularly in the area of sensor correlation, data fusion and situational awareness. Such scenario definition, modeling and T&E capabilities will become increasingly important for future aircraft where affordability, lethality, flexibility, availability and survivability considerations drive aircraft manufacturers toward more highly integrated and covert sensors and systems, and faster reaction weapons systems. Precise specification of systems of this level of capability, authority and probable automation (especially EW) is a prime requirement in minimizing development costs and ensuring that the aircraft is fit for purpose. This argument is equally applicable to the upgrading of current aircraft, where increased EW capability and/or integration of EW elements is popular world-wide and predicted to remain so. EO emitter data of the same fidelity as that for RF emitters is required to support the production of such EO scenarios.

Modeling Shortfalls

Three main issues currently affect models and simulators:

Emitter/threat system fidelity: Determination of the most cost-effective level of simulation (as distinct from emulation). CROSSBOW-S type accreditation is needed to ensure appropriate threat replication by simulators.

Scenario fidelity: This is a trade-off versus computing power. Current EW modeling tools and simulators cannot fully satisfy the requirements of fully realistic platforms' movement and those of emitter/threat system emulation in real time. The continuing increases in computing power and speeds offer much promise.

Modeling versus simulator capabilities: If the modeling system and RF/EO threat simulator form an integral part of the specification, design and development process, then it is important, if not crucial, that their capabilities in a number of specific areas are very similar if not the same. Inadequate similarity can lead to a substantial increase in the number of tests conducted or unnecessarily large error tolerance and/or pass/fail criteria.

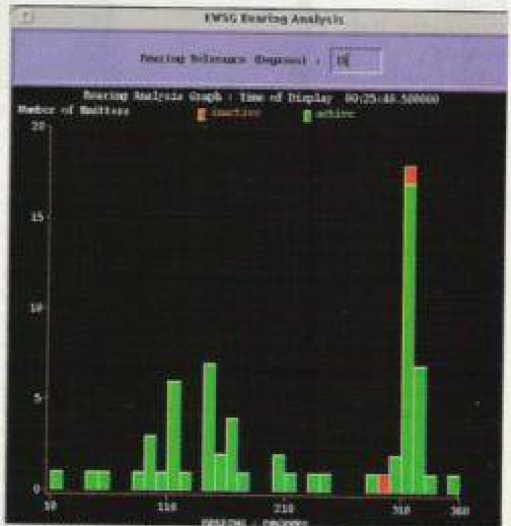


Fig. 2 EWES analysis outputs are used when full ESM system performance cannot be cost-effectively demonstrated with hardware tests.

Modeling Enhancements Needed

BAe has looked into the requirements for modeling and T&E capabilities necessary to support the concept development, specification, design and development of modern RF EW systems. More recently we have extended some of these investigations into the EO/laser arena. The RF items of particular interest are listed below.

- Terrain modeling: multipath
- Antenna patterns; near-field effects
- Third party tracking: chaff
- Atmospheric effects
- Repeatability and correlation
- Emitters/sensors on platforms
- Improved modulation on pulse
- ECM effectiveness
- Missile modeling

EW T&E IMPROVEMENTS

The development timescales of any avionics system is dominated by the T&E process, particularly so for EW systems. **Table 1** shows the typical development cycle of EW systems from requirements development to operational testing.

An internal study of EW systems integration over many years and a number of aircraft types shows that some 85% of the problems encountered could have been discovered much earlier in the development process, as shown in **Table 2**, by a combination of better T&E tools and techniques, and specification and design methodology. Although this underlined the possibility of verifying the majority of EW systems performance characteristics long before flight, through a combination of modeling, avionic rig and aircraft ground tests in anechoic chambers, it also showed that EW flight testing would still be needed — albeit at greatly reduced levels. To minimize development costs/timescales it is necessary to push as much as possible of the work from the flight trials phase to validated models.

Threat Simulators

The need for RF threat simulators for laboratory, chamber, flight-line and test/training ranges is widely recognized. Such simulation ranges from signal generators (some of which have very wide frequency range plus internal pulse- and frequency-modulation capability) to two of the more capable simulators currently available — the CEESIM (Combat EM Environment Simulator) by Amherst Systems Inc., and the AMES II (Advanced Multiple Environment Simulator) by Comptek Inc., Advanced Systems Div.

Having recognized the value of such simulators to the T&E process, it is important from a cost standpoint, (world-class RF threat simulators are multimillion dollar items) to ensure that the simulator is not over-specified. This precise definition of the EM environment and scenarios, as the complexity and specification of the simulator is required. By considering the scenarios and environment, the key cost drivers of the simulator can be specified:

- Number and frequency ranges of RF channels, yielding the pulse density capability (1-10 million pulses per sec for modern ESM systems).
- Number of simultaneous active emitters.
- "Concurrency" (how many of what type of emitter at any time) — a significant complexity/cost driver if a number of pulse Doppler radars, CW emitters and lower pulse repetition frequency emitters need to be simulated simultaneously.
- Number of emitters and platforms per scenario.

Table 1: EW Development Cycle

Air Force/Government Agency:
- -Operational requirement
- -Weapon system specification
- -Air vehicle specification

Aircraft Prime Contractor:
- -System/equipment specifications

EW Equipment Manufacturer:
- -Hardware/software specifications
- -Design/build/code hardware/software
- -Equipment and EW subsystem test

Aircraft/Systems Integrator:
- -Avionic integration rig & aircraft ground/flight tests
- -Corrections/modifications and specification changes if necessary

Air Force:
- -Operational evaluation leading to initial operation clearance

All Parties:
- -Changes/corrections leading to final operational clearance

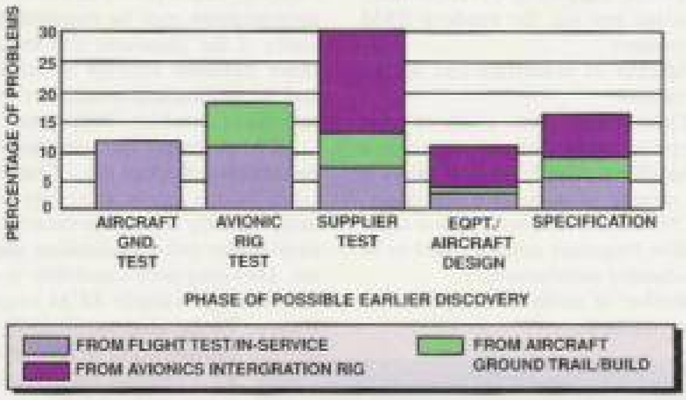
- Pulse percent drop-out tolerable by the EW equipment under test.
- Tolerable noise floor/bandwidth, intra- and interpulse noise levels, harmonics/spurious and intermodulation signals.
- RF output: 4-, 6- or 8-port direction of arrival; phase interferometer array.
- Power output, for post-antenna injection and free-space irradiation.

ECM Response Measurement

To evaluate ECM systems it is necessary to stimulate their receiver system, either ECM-specific or ESM in the case of some modern EW systems. For high-quality T&E work, it is necessary to simultaneously stimulate ESM and ECM receiver elements by post-antenna signal injection and antenna irradiation. To enable this, special simulator frequency sub-banding, output power and combining arrangements may be required, especially if the simulator can combine other onboard aircraft transmitters and harmonics/intermodulation products thus caused into its outputs.

ECM response measurement can be achieved through use of hardware such as spectrum analyzers and, more recently, by comprehensive and easy-to-use pulse modulation analyzers. However such capability is only suitable for simple ECM engagements. To be able to identify and capture ECM technique in an RF environment containing many pulsed/CW emitters and transmissions from other aircraft emitters, and determine that the correct technique has been applied against the appropriate threat is a complex task, well well beyond the scope of such equipment. For this task a new generation of ECM response measurement systems (RMSs) has been specified and ordered by BAe which will largely automate this task for laboratory and aircraft chamber/open air trials. Once again the environment and scenarios form the backbone of the specification of this equipment. By sampling the simulator output and the ambient RF environment, and through containing a predefined list of ECM techniques versus their RF parametrics, the specified RMS will be able to quickly identify ECM transmission by direction, time and emitter being jammed.

Currently the effectiveness of an ECM system is very difficult to measure absolutely. Survivability is a key issue in determining mission success and fleet affordability, but its quantification is made more difficult by the many interacting items affecting it (tactics, countermeasures deployment, EW support to the raid package, and so on). To quantify the survivability of an aircraft it is necessary to develop metrics which can be realistically specified and cost-effectively demonstrated with acceptable repeatability. Modeling has a role to play here but a more realistic way, which would have higher credibility air crews, may be using statistical models based on chamber tests of



Many of the problems encountered in EW system development can be detected early in the process with modeling and simulation.

ECM types and technologies. The metrics and qualification of aircraft performance could be determined via a modified threat simulator and RMS, where the threat simulator output is modified by the ECM transmitted from the aircraft. This topic of measures of effectiveness, has attracted much attention, particularly in the US where the AOC has conducted studies for the Department of Defense.

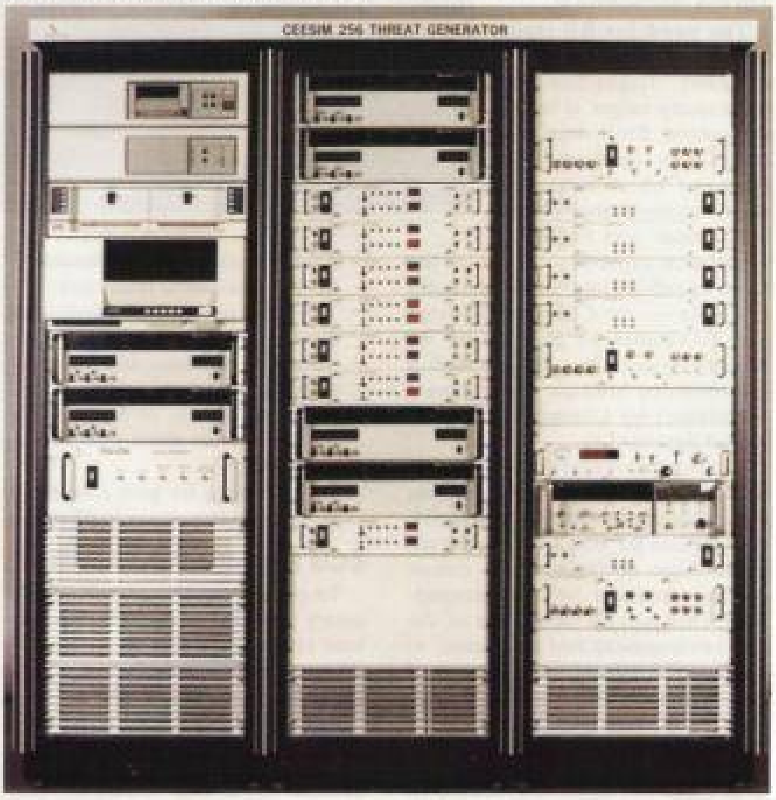
EW Test Data Analysis

A comprehensive tool is required for the parametric analysis of EW test data and its correlation with simulator and/or EW environment/equipment modeling outputs. Past lack of such capabilities has contributed to apparent differences between equipment and aircraft EW test results. Such a new tool has been ordered by BAe which will enable, in addition to the near real-time correlation capability of the ECM RMS, post-test analysis of aircraft avionics/EW equipment data and threat simulator data. This includes correlation of simulator-generated data with that of the EW system under test and subsequent time history and statistical analysis. Multi-parametric comparison of test and simulator data against engineer-defined correlation "windows" can also be automatically conducted. Together with precise scenario definitions, capable and realistic simulation, the ECM RMS, and a controlled anechoic chamber environment, this EW analysis tool, enabled by recent computing advances, will enable quantitative and repeatable EW equipment, subsystem and on-aircraft tests.

Correlated EO/RF Simulation

For T&E of EO equipment there is a need for the generation of appropriate stimulus for irradiation of sensors and post-sensor injection. In the case of lasers this is fairly straight forward for the post-sensor and direct irradiation of the sensor cases (via a closed "hood") for uninstalled equipment and avionic rig work. For the future, the use of multi-spectral sensors, data fusion, knowledge-based systems and fully integrated weapons systems on aircraft mean that correlated RF/EO stimuli will be required for testing EW systems and other sensors.

This poses a T&E problem since free-space firing of lasers poses a safety hazard and there are no established IR and ultraviolet (UV) simulators akin to the well established RF ones. Development work on such simulators is in progress in the US with the Real-Time IR Scene Simulator (RISS) by Amherst Inc., which can also provide a UV capability. Use of such a system in conjunction with an RF threat simulator and laser irradiation/control system, will enable controlled and simultaneous multispectral stimulation of aircraft forward looking IR, IR search and track, missile/weapon guidance seekers and passive missile warning systems. The use of such a sensor stimulation suite in conjunction with an anechoic chamber may offer significant test quality, timescale and cost improvements over the aircraft ground and flight trials currently required to develop and clear such systems into service.



The CEESIM RF threat simulator. (Amherst Systems photo)

IMPROVED METHODOLOGY

The thrusts of the previously described improved EW specification, design and T&E methodology are:

- Obtain the agreement of government agencies on the principle of precise RF/EO EW scenarios prior to contract. Work with those agencies and EW equipment suppliers to support timely production of scenarios.
- Continue driving more of the EW development process away from the highly expensive and time consuming flight test phase, through avionic rig, laboratory and aircraft in anechoic chamber trials, towards suitably validated modeling wherever possible.
- Continue investigations of shortcomings of present modeling and T&E tools/techniques, particularly those identified herein and especially those in the area of EO threat simulation and ECM effectiveness modeling/ test. Use this data to target improved capabilities to optimize development costs and timescales.
- Work with EW equipment suppliers to ensure affordable and mission-effective EW solutions for military aircraft, whether upgrades or on new airframes. Use of these industry capabilities can lead, in cooperation with government/air force agencies, to much increased quality specifications leading to aircraft weapon systems which affordable and fully fit for purpose.

CONCLUSIONS

BAe has learned many lessons from its involvement in EW. It has enacted most of the recommendations of internal study reports on its performance and this year has augmented upgraded environment and operational analysis modeling tools with major world-class EW T&E capabilities.

Issues involved in the EW specification through T&E process are highlighted and it is concluded that the dominant factor in the key areas of affordability, mission effectiveness and survivability is a precise definition of the EM environment in which the aircraft and its systems must operate correctly. A revized process is described which can yield evidence of performance at realistic cost and with maximum integrity.

With environment/scenario modeling tools and techniques in place, it is believed that air forces, industry and governments alike would all benefit from this precise and unambiguous definition of the RF and EO environments at the precontract stage for new or upgraded EW equipment. ■

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Note: This is an abridged version of an update to a paper presented to the 1995 AGARD Symposium on Environmental Factors in EW Related to Aerospace Systems, held in Italy. The full paper can be viewed on *JED* On-Line and also contains a section on Commonality of EW and EMC environment prediction needs, further figures, references and BAe contacts.

[From page 40] **AIEWS**

antimissile weapon system is subject to saturation, especially when fighting near a land-based adversary's coast. An integrated, modern EWS is a valuable equalizer that reduces the risk of surprise and saturation at one end of the engagement "stairway" and the risk of being hit by a "leaker" at the other. Second, the post-Cold War environment is involving the Navy in operations that can change from operations other than war to armed conflict in a matter of minutes. In these unpredictable, dynamic environments, the Navy usually will not have initial "escalatory dominance" due to political considerations, but American losses will put the President under considerable pressure to disengage or escalate. Navy officials agree that in such ambiguous circumstances, anything to reduce the unpredictability of attack is worth the investment. By developing the inherent modularity of the AIEWS and Nulka designs, a considerable economy of scale can be achieved while improving the capabilities of all major surface ships.

Cost? While the cost of implementing some of these upgrades is significant, it is small compared to the cost of replacing a scarce resource like a ship. Additionally, the personnel lost are essentially irreplaceable.

What's Needed? A Sense of Urgency. The current EWS is one of the oldest combat systems in the fleet, and in its present form gives few sailors a "warm, fuzzy feeling" about its reliability or effectiveness. Also, while most of the other Aegis Combat System components have been steadily evolving since the original baseline 1 cruisers of the early 1980s, EWS development has been repeatedly deferred due to higher priorities and/or insufficient funding. The surface combatant community must now overcome two decades of unfunded programs and a rapidly aging inventory of AN/SLQ-32A(V) and Mk 36 systems, both of which are out of production. Navy officers and naval systems analysts warn that without greater command interest in, and funding of, advanced EWS components such as AIEWS and Nulka, the limited effectiveness, reliability and integration of these increasingly vital and cost-effective systems will decline into obsolescence. ■

"Gators" present a tempting target and will need EW to protect them. (Ingalls Shipbuilding photo)

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Multi-Sensor Systems and Data Fusion for Telecommunications, Remote Sensing and Radar

(les Systèmes multi-senseurs et le fusionnement des données pour les télécommunications, la télédétection et les radars)

Papers presented at the Sensor and Propagation Panel Symposium, held in Lisbon, Portugal, 29 September - 2 October 1997.

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AIRCRAFT SENSOR DATA FUSION: AN IMPROVED PROCESS AND THE IMPACT OF ESM ENHANCEMENTS

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SUMMARY

British Aerospace Military Aircraft and Aerostructures (BAe MA&A) has conducted various studies on the topic of Data Fusion. This paper highlights developments which, it is thought, offer a significant step towards optimum situation awareness. It examines sensor data quality, the fusion process and required improvements, and proposes a method for improving the quality of the resultant threat identification function. The paper also examines the key issues affecting the quality of track data fed into the fusion process by Electronic Support Measures systems (ESM), the prime contributor of threat identity data. Emitter recognition and location issues are discussed and potential routes are proposed to attain the necessary performance increases to support optimum situation awareness.

1 INTRODUCTION

Swift and unambiguous identification of hostile weapon system type and location in tactical scenarios is fundamental to aircraft mission success and survivability. To attain the highest probability of mission success the same identification and classification quality is required for all players in the scenario, whether hostile, friendly or neutral.

The fusing of data from multiple on-board multi-spectral sensors and other off-board data sources offers great potential for achieving high grade situation awareness. Example on-board sensors include radar, IFF, ESM, Forward-Looking and Search/Track Infra-Red (FLIR/IRST), LIDAR and Missile Warning Systems. This fusing corresponds to optimisation of own weapon targeting, threat evasion and countermeasures capabilities. These aspects can lead to improvements in aircraft lethality and survivability which, in turn, influence affordability, flexibility and availability. These five factors will be, arguably, the key product differentiators in the military aircraft market place of the future.

This paper defines 'Identification' in the military sense and discusses current identification processes and limitations. It describes the Identity Fusion Process and the contribution of various levels of ESM capability to that process. Potential improvements to identification are then described, comprising an improved fusion process and those relating to enhanced ESM performance. Identity Fusion Process simulation results are presented for different ESM capability levels, conclusions are drawn and a way ahead proposed. Although the issues addressed are applicable to all classes of military aircraft, the focus of work to date has been on fighter-sized aircraft of the present and future.

2 IDENTIFICATION

Reliable identification of own forces, threats, non-combatants and targets poses problems on any battlefield. This is particularly so in the air where participants in the battle may be highly dynamic and where own forces and hostile forces may be interspersed.

In order to avoid increasing the risk of being the perpetrator or the victim of fratricide, aircraft must improve their abilities to declare their identity to friendly forces and to recognise the declarations of others. To avoid collateral damage and casualties among non-combatants the ability to identify an intended target or a major threat positively before weapon release must be improved. The potential resources available to an identification system and the contributions they make to tactical situation awareness are summarised in Table 1.

When own forces are well separated from enemy forces and non-combatants, they may be identified by their actions conforming to some known mission plan. If a package encounters a friendly unit where the mission plan says it will be and at the right time, the task of the identification system will be relatively easy. By a similar argument, if forces are engaged in activities which do not correspond to the mission plan or any filed flight plan, they must be regarded as suspect. However, lack of adherence to a known plan is not a conclusive indicator of hostility.

Own forces may be identified by the ability to sign on to and exchange information with data communications networks and their ability to make the right responses to Co-operative Target Identification (CTI) systems. Again, the inability to make the appropriate communications and responses adds weight to the supposition of hostility.

For all participants and non-combatants, sensor data from Non Co-operative Identification (NCI) systems or from imaging systems may contribute to an eventual successful identification and, if they are making Radio/Radar Frequency (RF) emissions, these may be identifiable by the ESM. These latter approaches attempt to recognise the unit in question by its appearance or by the characteristics of the RF equipment it carries. However, the changing European political situation and the global armaments market increase the likelihood that similar units will fight on both sides of any conflict and so decrease the confidence which can be placed in these approaches.

When own forces are interspersed with enemy forces, the task of reliable identification becomes more difficult. Units which are identified by their participation in data communications networks can still be identified reliably if they are capable of declaring their position with high accuracy (*e.g.* by using the Global Positioning System), provided the observer knows its own position equally accurately. Interspersing of forces may pose difficulties for CTI and NCI systems if the sensor resolution of the system is poor and/or own and enemy forces lie in close proximity.

It is reasonable to assume that the ESM will be optimised to identify major threats from the RF emissions that they make. Traditionally, the ESM has produced coarse direction and estimates together with increasingly reliable identity statements and this combination of data qualities poses particular problems for the Sensor Fusion (SF) process. The identity statements are of increasingly high value but, in crowded scenarios, cannot currently be unambiguously associated with an individual track. These problems and potential solutions to them provide the subject matter for this paper.

Paper presented at the AGARD SPP Symposium on "Multi-Sensor Systems and Data Fusion for Telecommunications, Remote Sensing and Radar", held in Lisbon, Portugal, 29 September - 2 October 1997, and published in CP-595.

3 CURRENT PROCESSES AND LIMITATIONS

This section will look at the identification process from two points of view. Firstly, it considers how a conventional SF system brings together the identity information available to the aircraft. Secondly it considers current ESM and the ways in which they derive platform identity and location.

3.1 The Sensor Fusion Process

The SF process exists to gather together all the situation data arriving at the platform in question and to consolidate it into a single tactical picture. The platform which is of interest here is a fighter aircraft engaged in an air defence mission and the following assumes that application. SF may be regarded as a two stage process, see Figure 1. The first stage is tracking, during which all the sensor measurements referring to a particular platform are brought together over time. This gives the most complete and accurate estimate of the platform's position, motion and status that the measurements allow, along with some definition of the uncertainty in that estimate. A tracking process may use measurements from one or more sensors and the sensors may be distributed over multiple aircraft and depend on communications links.

If it were possible to gather all the sensor measurements at a single tracking process in a timely and reliable way, a single track database would be produced and the SF process would be complete at this stage. In practice, the constraints on the system are too great and this does not happen. So, at the end of the tracking stage several tracking processes will have produced their own database, each with its own view of the world, which then must be combined.

The second fusion stage, Track-to-Track Fusion, exists to combine these track databases into a single fused database. To do this it must perform the following three tasks:

- It must align the tracks to the same spatial axis set and time.

There is no guarantee that each tracker will use the same axis set. They may measure very different platform attributes and have very different points of view, especially when the sensors they serve are carried on separate aircraft. So the Track-to-Track Fusion process must perform any transformations necessary to align the platform data and corresponding uncertainty definitions to a common axis set. Also, each track will have received its last update at a different instant in time. So track data must be extrapolated to account for motion since it was last updated and each uncertainty definition must be modified to account for possible manoeuvres or changes in status since the update.

- It must deduce the number of targets giving rise to the data and the platform from which each track arose .

When data first arrives at the Track-to-Track Fusion process the number of targets is unknown. If two sensors each reported two targets, and if the reporting of false targets is sufficiently unlikely for us to ignore it, we must still consider the possibilities that there are two, three or four targets being detected, jointly, by the sensors. To do this we calculate the likelihood of each possibility and choose the most likely one. This process is commonly referred to association or correlation. Usually, this stage of the process will attempt to optimise some figure of merit for the association process which is linked to the likelihood of making the right choice. Firstly, an algorithm would mark each pair of tracks arising from different trackers as 'feasible' or 'not feasible' based on some statistical hypothesis test. Secondly, it would calculate the figure of merit for each 'feasible' pair. Finally, it would perform a search through the possible combinations of 'feasible' pairs and choose the one giving the best overall figure of merit. Some implementations shorten this process by performing these stages for new tracks only. For established tracks in such implementations, existing solutions would be retained until new data were received in direct contradiction to them.

- It must form joint tracks and joint identity statements for targets reported by more than one source.

The formation of joint tracks can range from a simple approach, which selects the best single track to represent the associated class, up to more complex approaches which calculate an optimal joint track using an algorithm based in estimation theory (*e.g.* minimum mean square error). Similarly, approaches to joint identity estimate formation can range from simple voting to algorithms based in statistical theory (*e.g.* Dempster's orthogonal sum).

A conventional approach to the implementation of Track-to-Track Fusion would adopt a process breakdown similar to the functional one described above and represented in Figure 1. However, this approach has limitations[19]:

- The ability to produce an unambiguous solution to the association question depends on the scenario. When the targets are dispersed and tracks from different targets are unambiguously separate, no problems arise. Similarly, when similar targets are grouped very tightly so that tracks from the same class may be interchanged without affecting the solution, no problems arise. However, when dissimilar targets lie close together incorrect associations may be made which affect the quality of the fused picture. This is discussed by Blackman [1]. In terms of the likelihoods described above, there would be conflicting feasible solutions with similar likelihood scores.
- The estimation process may be based on the assumption that data has been correctly associated and may attempt optimal combination of the data on that basis [1,2,3]. Processes of this kind, applied to incorrectly associated data, may produce meaningless results. Paradoxically, it is the 'optimal' algorithms which are the least robust in this respect because they rely most heavily on the assumption of correct track-to-track associations.
- When incorrect associations arise, they may change over time and with them the output of the estimation processes. This in turn leads to incorrect and changing information displayed in the cockpit with errors that move from platform to platform over time.

Data from the ESM is particularly prone to problems of this sort because, in present day systems, it tends to produce tracks with the coarsest positional accuracy. At the same time, the identity statements it produces may be the most specific and accurate available within the avionics system. Thus, there is a great incentive to use them. The result, when unfavourable scenarios are encountered, can be incorrect and changing identity statements displayed in the cockpit. There are several ways in which these limitations might be overcome. Two are considered in this paper:

- improvements in sensor accuracy and resolution, which would restrict the problem to more distant, tightly-grouped formations of targets.
- the use of algorithms which recognise the potential for ambiguity and take it into account, which would prevent the generation of incorrect and unstable solutions.

3.2 ESM, its Contribution and Limitations

Most threat weapon systems have a RF targeting and/or guidance component, usually in C-K band (0.5-40 GHz) and predominantly in E-J band (2-18 GHz), although there is now an increasing number of laser-only or laser-augmented systems. For the systems where RF is employed, the primary on-aircraft measurement and warning sensor is the ESM. In this paper the term ESM is taken to mean any level of Electronic Warfare (EW) antenna/receiver system capability; from simple Radar Warning Receiver (RWR), through conventional ESM, to the most complex (and costly) Electronic Intelligence (ELINT) equipment. A factor in common between RWR, ESM and ELINT is their function of detecting and processing radar signals. The main differences are:

- RWRs are used primarily for threat warning.
- ESM is used for threat warning, the detection and identification of non-threat emitters, such as surveillance radars, and to determine emitter location. An ESM system designed primarily for emitter location is called an Emitter Location (EL) or Locator System, such as that fitted to the Electronic Combat and Reconnaissance (ECR) Tornado.
- ELINT is used for the detection, recording and analysis of radar/radio signals as well as locating emitters. It may be implemented by the addition of a recording and analysis capability to ESM, but often uses more sophisticated receiver systems. The emitter data resulting from ELINT analysis can be entered into the data bases which are needed for reprogrammable EW systems.

The data that ESM can contribute to the fusion process are:

- Azimuth Direction of Arrival (DOA) and, in some instances Elevation DOA,
- Emitter, mode and associated platform identification, each with a recognition confidence factor,
- Time of Arrival (TOA) and Range to the emitter, and
- Priority, if the emitter is a threat.

The ESM, dependent upon its capability, may also provide measured emitter RF parameters (*e.g.* the ELINT fundamental parameters of frequency, Pulse Width and Repetition Interval, received power, and scan time/rate) and EL (from DOA and range). Derived parameters include RF type (fixed, hopper, deviations, *etc.*), PRI type (fixed, jitter, stagger, positions, elements, *etc.*) and Scan type (circular, conical, *etc.*). The accuracy of DOA, quality of and confidence in the above identification, and speed with which the ESM determines them, determine their importance to the fusion process. Probability of signal Intercept (POI), whilst crucial to the emitter recognition process, is not *per se* an input to the fusion process. POI is usually specified for an ESM; with typical values of approaching 100% for modern ESM. These factors are also arguably the key performance and cost differentiators between the sub-classes of ESM.

DOA Determination

ESM systems use DOA determination techniques which are based upon the measurement of some combination of amplitude, phase and time of arrival of an emitter's RF signal at a number of co-located and/or remotely located receive antennas on the airframe. Current techniques are listed in Table 2 and are adequately described in a number of texts, *e.g.* [4]-[6]. The resulting DOA accuracy is primarily a function of antenna type and locations, combined with receiver measurement accuracy of frequency, time and phase. Table 2 summarises typical current DOA accuracies for the main techniques. It should be noted that the absolute accuracy is often different for frequency sub-bands, dependent upon the technique and receiver combination(s) used. Newer DOA and EL techniques, *e.g.* differential Doppler, are discussed later.

Emitter/Platform Recognition

Significant commonality of RF parametrics of hostile and friendly radars limits the ability of current EW systems to provide the aircrew with unambiguous identification of the illuminating emitters. This is exacerbated by errors in RF parametric measurements and shortcomings of intelligence data programmed into the ESM. These issues, which are expanded upon in [7], have an adverse impact on situation awareness and the timely deployment of electronic countermeasures. There are four inter-related issues which need to be addressed if improved situation awareness is to be achieved and increased platform survivability ensured. These are the de-interleaving of incident RF pulse trains, the resolution of the fundamental problem of emitter ambiguity, the precise identification of platforms, and the potential benefits of the preceding items on countermeasures effectiveness. Of these four, emitter ambiguity is seen as the main issue and its resolution may lie in improved measurement and processing of intra-pulse modulation on signals.

Dense (>1 MPPS) RF environments can be achieved nowadays in certain frequency sub-bands, especially now high-PRF pulse-doppler radars are common. Typical current ESM can, within the very short time allowed to cater for countermeasure engagement/dispensing, only offer track file outputs as a list of potential solutions to which emitters it thinks it has seen, prioritised according to some pre-set rules *e.g.* hostile emitters are at the top of the list. Where association of these emitters to a platform can be made by the ESM, that too may be declared on the track file. The confidence of the ESM in its determination of the probability of a given emitter and platform declaration being correct is also flagged per emitter. For current systems this confidence factor is rarely unity for other than the simplest of RF scenarios.

Electronic 'fingerprints' of emitters and emitter types are discussed in a number of texts *e.g.* [8]-[10]. Although there are differing interpretations of the term 'fingerprinting', it means the use of a unique set of measurable parameters which enables either differentiation between emitter types (*e.g.* by features peculiar to the radar transmitter *type*), or between emitters of the same type, or indeed (and ideally) both. This topic is discussed later. A high level of emitter 'fingerprinting' can be achieved using current RWR/ESM (as opposed to ELINT systems), but only where the RF environment is relatively limited. [10] describes such an eight emitter, I-band scenario where, with one exception, the emitters could be unambiguously identified using today's ESM technology capabilities of: RF resolution (5 MHz), PW resolution (50 ns), TOA resolution (50 ns) and Scan resolution (4 ms).

Another problem of ESM capability limiting its usefulness to the determination of a real-time tactical picture is the update rate of track file information. The ideal ESM performance requirement is to see only the leading edge of the first RF signal (pulse or CW), and to instantly and unambiguously recognise the emitter, classify friend or foe and instigate crew notification, chaff dispensing and/or ECM engagement. In reality a few pulses and a few seconds are required to achieve the above with any degree of confidence. In order to provide sensible polar-type spokes on a CRT display the identified emitter, its bearing and signal strength need to be displayed for a finite period of time. To cater for scanning or slow rotation rate emitters, where there may typically be up to 10 seconds between RF 'wipes' across the ESM antennas, the displays and appropriate countermeasures engaged may be kept on for the duration - until the emitter is definitely no longer illuminating the host aircraft. This can lead to the contents of the track file indicating emitter presence for some number of seconds after it has actually ceased to pose any form of threat, a limitation for fighter operations.

Emitter Location

The objectives and required accuracies of EL are summarised in Table 3. A number of conventional techniques exist for EL [5], [4], although only three are strictly applicable to military aircraft in the wingspan/length range 15 m (fighters) to 35 m (maritime patrol aircraft). These techniques are:

- Azimuth/Elevation: Ground emitters can be located instantaneously, assuming the use of aircraft altitude and reasonable DOA accuracy, either amplitude comparison (low cost) or interferometer (high cost) direction finding techniques. The down- and cross-range errors are a function of DOA errors, height accuracy and range to emitter. Table 4, adapted from [5] gives an indication of the down-range errors for two altitudes, using an early generation 3 azimuth, 3 elevation spiral antenna interferometer array. The ranging accuracy of this technique is best at high altitude (large depression angles) and degrades rapidly at low altitudes - an appreciable limitation for low level operations.
- Triangulation: The aircraft takes azimuth (or rather bearing) measurements at regular intervals of a few seconds, and uses triangulation and estimation algorithms to arrive at an accurate EL within a few seconds. This technique is more applicable to the ECR/ELINT role than to the fighter/bomber application, as it is not a forward-looking technique. It is, however, used on a number of current systems, e.g. that on the ECR Tornado, and requires very accurate DOA to achieve useful ranging against airborne emitters. Fig. 9 of [5] gives an indication of range uncertainty using this technique and two examples from that figure indicate the limitations of this technique for fighter applications as follows. To achieve a reasonable range uncertainty (say 3%) with an EL system with 1° DOA accuracy, at an own-aircraft speed of 400 Kts and at a nominal emitter to aircraft range of 15 n. miles, then one measurement would be required every 2 sec. for 60 sec. To reduce the required measurement time to that relevant to fighter operations (~5 sec.), a DOA accuracy of 0.1° would be required to achieve even 20% range uncertainty.
- Time Difference of Arrival (TDOA): Traditionally this has been a multi-platform technique, but can be implemented successfully on a large aircraft, now that TOA measurement systems with 1-5 ns resolution are available. It is a complex technique and technology, yielding high accuracy with high speed - but at high cost. It is unlikely to be feasible on a fighter-sized airframe due to the need for very wide spacing of antenna to form TDOA measurement baselines.

In each of the above techniques, various methods can be used to resolve location ambiguities and reduce overall emitter position error. One of the simplest methods is range estimation by the comparison of measured signal power against that stored in the ESM's emitter database for the Effective Radiated Power of that emitter. Paradowski [11] discusses EL techniques and algorithms, and includes a number of these methods.

4 POTENTIAL IMPROVEMENTS TO THE IDENTIFICATION PROCESS

This section will look at possible improvements to the identification process. Firstly, it considers how the SF process might better extract identity information from the ESM by allowing for ambiguity in its calculations. Secondly, it considers future ESM and the ways in which the quality of platform identity and location statements might improve, so improving the intrinsic capabilities of the system to resolve ambiguity.

4.1 The Improved Sensor Fusion Process

We have developed an approach to Identity Fusion which takes account of the ambiguity in the Track-to-Track association solution. The approach calculates the true probability of each identity for each track. When ambiguity is present it results in a solution which is offered with lower confidence than a conventional approach but which is stable and relatively free from error. In the absence of ambiguity, it produces a solution which is indistinguishable, numerically, from that produced by the conventional approach. We will refer to the new approach as Joint Probabilistic Identity Fusion. We propose two changes to the conventional SF process of section 3:

- The ESM 'tracks' will undergo a separate Track-to-Track Fusion process.

In particular, the alignment and association processes will be performed with respect to a partial fused picture comprising all non-ESM data. This may be expressed in terms of probabilities. Previously, we calculated a figure of merit which allowed us to maximise the likelihood of choosing the correct set of associations. The probability distribution, $P(\mathbf{X})$, that our fused picture is based on the true set of associations is written:

$$P(\mathbf{X}) = \prod_i P(\mathbf{x}_i | \mathbf{Z})$$

where $\mathbf{X}$ is the fused picture, $\mathbf{Z}$ represents the set of single source tracks and $\mathbf{x}_i$ is the i^{th} fused track in $\mathbf{X}$.

In the improved process we calculate:

$$P(\mathbf{X}') = \prod_i P(\mathbf{x}'_i | \mathbf{Z}_k)$$

and

$$P(\mathbf{X}) = \prod_i P(\mathbf{x}_i | \mathbf{X}', \mathbf{Z}_e)$$

where $\mathbf{X}'$ represents the partial fused picture, $\mathbf{x}'_i$ is the i^{th} partial fused track in $\mathbf{X}'$ and $\mathbf{Z}_e$ and $\mathbf{Z}_k$ represent the set of ESM tracks and the set of other tracks respectively.

This change, in itself, does not improve matters greatly. The true value of $P(\mathbf{X})$ should not change. However, it imposes a processing structure into which our Joint Probabilistic approach fits neatly. Thus, it enables us to calculate a better approximation to $P(\mathbf{X})$.

Also, it is worth noting that situations leading to uncertainty about $P(\mathbf{X}')$ are relatively rare and we are able to obtain a good approximation to this distribution whilst avoiding a large amount of redundant processing. The key factor in the accuracy of the association process is the distribution of physical targets and this change delays ESM association until the most complete statement of this distribution is possible.

- Association and identity estimation will adopt a Joint Probabilistic approach [2].

This means that, during association, instead of associating ESM tracks with targets on a one-to-one basis, we will produce probabilities that each ESM track arose from all of the targets present in the scenario. We can calculate this with a high degree of certainty using standard statistical theory. What we cannot do with any certainty is choose which one platform the ESM track arose from when these calculations yield similar probabilities for several tracks. The advantage of this approach is that we avoid this choice.

Previously we chose a set of associations, Θ, such that

$$\Theta = \arg\max_j \{P(\mathbf{X}|\Theta_j)\}$$

where Θ_j is the j^{th} feasible set of track-to-track associations. Then $P(\mathbf{X}|\Theta)$ was our (often poor) approximation to $P(\mathbf{X})$.

In the improved process, we continue to use this approach for non-ESM tracks to obtain the set of partial associations Θ' noting that $P(\mathbf{X}'|\Theta')$ is nearly always a good approximation for $P(\mathbf{X}')$.

For ESM tracks we calculate the probability:

$$\theta_{il} = p(\mathbf{x}_i = \mathbf{z}_{el})$$

where $\mathbf{z}_{el}$ is the l^{th} ESM track.

During identity estimation, instead of combining associated identity statements under the assumption of correct association, we will combine all ESM identity statements into each platform, weighted by its probability of association.

Previously the probability of each identity was calculated for fused track i using Bayes rule:

$$p(y_m|\mathbf{Z},\Theta) = p(y_m) \times \prod_n p(y_m|\mathbf{z}_{in}) \div p(\mathbf{Z})$$

where y_m is the m^{th} feasible identity and $\mathbf{z}_{in}$ is an identity statement from sensor n associated with fused track i by Θ. Then the identity of track i was chosen

$$\mathbf{i}_i = \arg\max_m \{p(y_m|\mathbf{Z},\Theta)\}$$

and a declaration was made provided the associated probability exceeded some threshold. This worked well only when $P(\mathbf{X}|\Theta)$ proved to be a good approximation to $P(\mathbf{X})$.

In the improved process the probability of each identity is calculated:

$$p(y_m|\mathbf{Z},\Theta',\theta)$$

$$p(y_m) \times \prod_{n \neq e} p(y_m|\mathbf{z}_{in}) \times \sum_l [p(y_m|\mathbf{z}_{el},\theta_{il})] \div p(\mathbf{Z})$$

where $\mathbf{z}_{el}$ the l^{th} ESM track. Thus, the probability of each identity no longer depends on the unreliable ESM associations because we have not chosen ESM associations on the basis of questionable data. The most likely identity will be chosen :

$$\mathbf{i}_i = \arg\max_m \{p(y_m|\mathbf{Z},\Theta',\theta)\}$$

and a declaration made or withheld in the same way as before.

This change calculates the true probability of each identity class for each platform. When no ambiguity is present, this will produce the same clear identity statement as before. When ambiguity is present it will be reflected in a broader spread of probable identity classes for each affected platform and as a result it will be obvious that a confident statement of identity cannot be given. However, it may be possible to make more general statements of identity in these circumstances.

The improved SF process may be visualised, see Figure 2. Where a conventional process would produce incorrect and unstable identity statements, we assert that the Joint Probabilistic Identity Fusion process will allow correct and stable generalised statements to be made.

4.2 Improvements via Enhanced ESM Performance

The contribution of ESM to the data fusion process is currently undergoing a step improvement. Publications by ESM suppliers suggest that the ideal ESM performance of instantaneous unambiguous identification and exact spatial location of pulse/CW emitters may soon be feasible on any size of platform. Moreover, the technologies and techniques currently under development appear to eventually be applicable as relatively low cost retro-modification 'kits' to existing capability RWR/ESM. The three key development areas are:

- Advanced Combinational EL Techniques: Ongoing advances in processing speeds and processing technologies now enable combinations of classical DOA and EL techniques, in order to optimise EL performance, minimise errors and mitigate the shortfalls of individual techniques. A good example of this is the integrated ranging technique in the Litton Digital Receiver [12], developed under the U.S. Precision Location And IDentification (PLAID) programme [13]-[14], which combines long baseline (phase rate of change), TDOA, frequency Doppler and time Doppler. These combinations can also include novel techniques such as Differential Doppler [4], [11], which have only become realistic techniques for fighter aircraft with the advent of receivers capable of measuring frequencies to fractions of Hz [14].
- 'Fingerprinting': Current ESM have limited capability to quickly and unambiguously identify emitters, especially when the RF environment is dense. A number of agencies and research programmes have been addressing this fundamental limitation for many years. Only recently have technological developments occurred which now are believed to offer hope of achieving the above goal. During this time the proliferation of high performance and complex (multi-mode, high PRF) radars has continued, with a 1996 estimate of 4030 different radar types world-wide [15]. Close to ideal ESM capability is now believed to be feasible by using digital receivers (see below) together with combinations of analysis techniques such as classical parameter (frequency, PW, PRI *etc.*), clock de-interleaving, fine grain Intra-Pulse, Unintentional Modulation on Pulse and EL analysis [13]-[14]. Supplier claims [16] suggest that, by the year 2010, 100% of emitter ambiguity resolution may be resolvable as shown in Table 5, where SEI = Specific Emitter Identification.
- Digital Receivers: To enable the above, receiver/measurment system improvements have been required. A new generation of digital receivers have thus been developed, of which [12] and the Lockheed-Martin Passive Ranging Subsystem (PRSS) [17] are examples, approach readiness for in-service use. These have very high measurement accuracies/resolutions for frequency (<10 Hz), phase (few degrees), TOA (2 ns or better), PRI (sub-ns) and amplitude (<1 dB).

Other potential ESM enhancements include:

- higher receiver sensitivity (better than -60 dBm [10]), improved signal-to-noise and the use of more efficient spiral antennas, *e.g.* the spiral microstrip type [18]. These would equate to improved emitter detection range and could further assist in ambiguity resolution by comparison of measured signal power *vs.* emitter database effective radiated power.
- use of artificial intelligence (Knowledge-Based Systems), *cf.* Ch.8.7 of [6]. At the simplest level, ambiguity resolution could be aided by masking by logical aspects, *e.g.* a) ship radars don't fly; and b) if it's in front AND is above you AND has a high PRF AND is coming this way THEN it's very highly likely to be a threat!

5 SIMULATION RESULTS

Detailed simulations were performed and two scenarios were examined, see Figure 3. The first is an unambiguous Combat Air Patrol (CAP) scenario capable of resolution using a conventional SF algorithm and current ESM. The second is an ambiguous CAP scenario which is not. The scenarios are identical with the exception of the addition of a bomber formation to the latter, which is sufficient to introduce the ambiguities discussed previously. Each CAP aircraft is equipped with Radar, IRST and ESM, and they exchange track information using data links. The Radars are assumed to contribute identity information in the form of a size estimate and a Jet Engine Modulation measurement. Data link tracks contain the transmitting platform's estimate of identity based on locally sensed data. The ESM identity statements are assumed to be the most specific and accurate in the system.

Performance was measured using the conventional Identity Fusion process, as described in section 3, and the Joint Probabilistic Identity Fusion process and with 'current' and '2010' ESM. Results are presented as plots of % tracks a) correctly identified (*i.e.* Tornado, Hawk *etc.*), b) placed in the correct class (fighter, bomber *etc.*), c) not identified, and d) wrongly identified or classified. Basic identification as hostile, friend, neutral was not simulated but the same principles apply. The results indicate the performance of the system with respect to identification of hostile aircraft. In all cases, friends reported their identity and position (with GPS accuracy) *via* data links and were unambiguously identified.

Unambiguous scenario results:

- Figure 3.1 shows the performance of the conventional SF process with the 'current' ESM system. After ~30 seconds of the scenario every track was correctly identified or classified. After ~100 seconds it was possible to identify every platform.
- Figure 3.2 shows the performance of the improved SF process with the 'current' ESM. There is a slight improvement but the result is broadly similar to Figure 3.1.
- Figure 3.3 shows the performance of the conventional SF process with the '2010' ESM system. This combination of systems identifies the targets quickly and fully.

Ambiguous scenario results: The time windows, which are different for each scenario, were those during which sensor coverage of the hostile aircraft was or approached its maximum and thus most revealing of the SF process performance.

- Figure 3.4 shows the performance of the conventional SF process with the 'current' ESM system. This combination never fully identified the hostile targets. 20% or more of the identities were in error and the errors were unstable, moving from aircraft to aircraft.
- Figure 3.5 shows the performance of the improved SF process with the 'current' ESM. All aircraft are correctly identified after ~80 sec.
- Figure 3.6 shows the performance of the conventional SF process with the '2010' ESM system. Here, all targets were identified but the time taken (~120 seconds) to resolve all identities was longer than in Fig. 3.5. The simulation used did not Kalman filter the ESM tracks prior to Track-to-Track association. Had it done so, performance would have been better because the resulting sight-line angular velocity information would have made it easier to discriminate between the tracks and convergence to the fully identified state would have been quicker.

6 CONCLUSIONS AND WAY AHEAD

The simulations showed that the proposed Joint Probabilistic Identity Fusion process and the '2010' ESM system were both capable of resolving the kinds of ambiguity which would defeat conventional systems. Combined, they would be capable of dealing with greater and more complex ambiguities. They also showed that the Joint Probabilistic approach to Identity Fusion also promises improved performance in aircraft with an earlier generation ESM. Suggested future research paths are:

- examination and refinement of this approach using real sensor data, in a suitable rig and (subsequently) aircraft environment.
- further development and refinement of the apporach and algorithms *via* inclusion of a model of a year '2010' ESM.
- inclusion of 'Smart' sensor systems in the simulation. In our simulations, the opposing radars were dumb and noisy. Smart sensor systems which integrate data from multiple sensors and make Radar emissions only when it is absolutely necessary are feasible using today's technologies. Such systems will increase the uncertainty surrounding ESM data by reducing the data rate and will militate further for the use of an approach to Identity Fusion like the Joint Probabilistic one described here.

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Table 1: Identification System Resources

Resource	Own Forces	Threats	Targets	Non-Combatant
Mission Plan	o	o	o	o
Communications with own forces.	*	*	*	*
IFF (CTI)	o	o	o	o
Long range imagery	o	o	o	o
RADAR(NCTI)	o	o	o	o
LIDAR(NCTI)	o	o	o	o
ESM	*	*	*	o
Self-defence systems		*		

* .. may provide conclusive identity statement.

o .. can contribute identity information.

Table 2: Direction of Arrival Technologies and Accuracies

(developed from [4] and [5])

Antenna Configuration	Typical r.m.s. Accuracies	Comment (regarding application to aircraft)
Amplitude Comparison	3-15°	Minimum capability of all sub-classes of ESM.
Phase interferometer	0.1-3°	Forward coverage, azimuth only (some elevation also).
Spinner	2-5°	Not appropriate to fast jets.
Multibeam	1.7-2°	Naval and ground vehicle applications.
Time Difference Of Arrival	<2°	Complex; needs large airframe for highest accuracy.

Table 3: Implications of Emitter Location Objectives

(from [4])

Objective	Enables	Required Accuracy
Electronic Order of Battle	Location of emitter types associated with specific weapons and units show enemy strength, deployment and mission.	Medium: 1km
Weapon sensor location (Self-Protection)	Focusing of jamming power or manoeuvre for threat avoidance	Low: general angle and range ~5km
Weapon sensor location (Protect Friends)	Threat avoidance by other friendly combatants	Medium: ~1km
Enemy asset location	Narrowed recce search or handoff to homing devices	Medium: ~5km
Precision target location	Direct attack by 'dumb bombs' or artillery	High: ~100m
Emitter differentiation	Sorting by location for separation of threats for identification processing	Low: general angle and range ~5km

Table 4: Typical Position/Range Determination Accuracies using conventional single-aircraft EL Techniques

(Adapted from [5])

	Range Error			
Plan Range n. miles	Altitude = 1 nm (6076 feet)		Altitude = 4 nm (24306 feet)	
	n. miles	%	n. miles	%
5	0.43	8.6	0.07	1.4
10	1.75	17.5	0.4	4
20	7	35	1.7	8.5
30	15.7	52.3	3.9	13
40	-	-	6.9	17.3
50	-	-	10.9	21.8

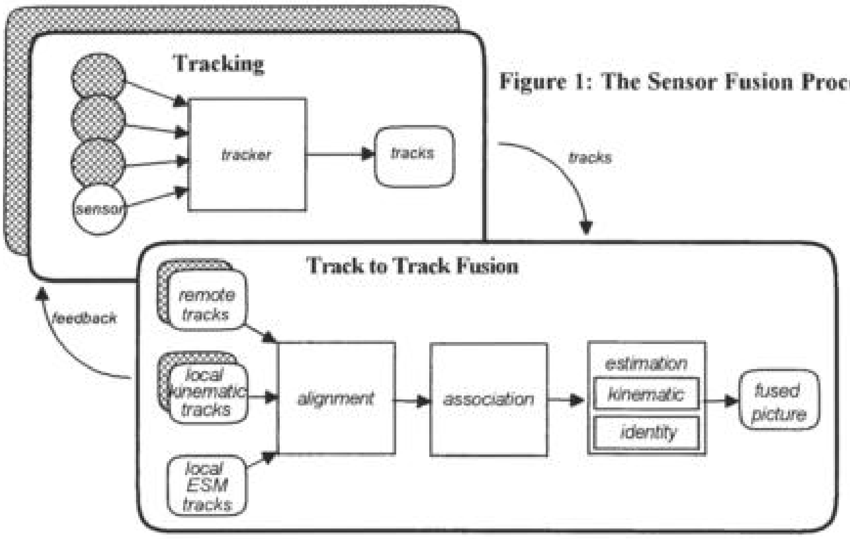


Figure 1: The Sensor Fusion Process

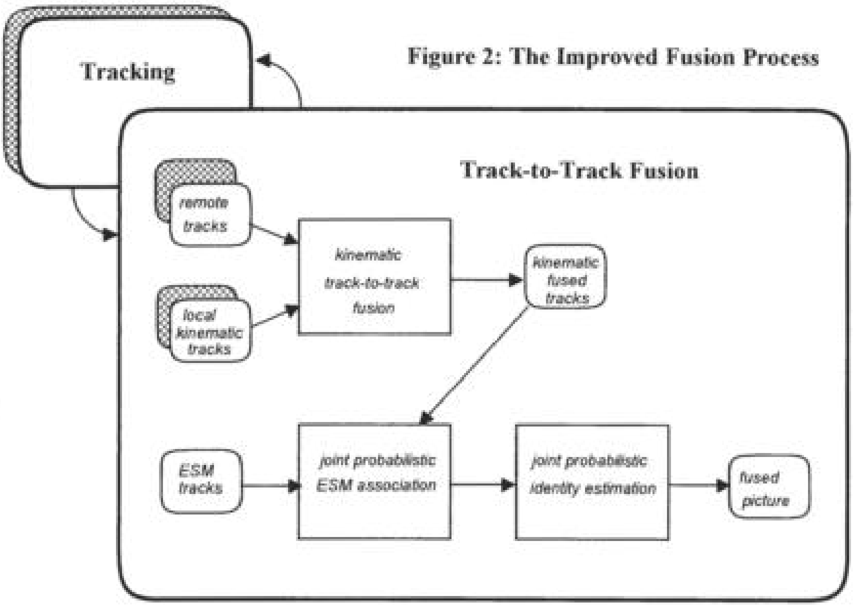


Figure 2: The Improved Fusion Process

Table 5: Year 2010 Scenario Ambiguity Resolution

(from [16])

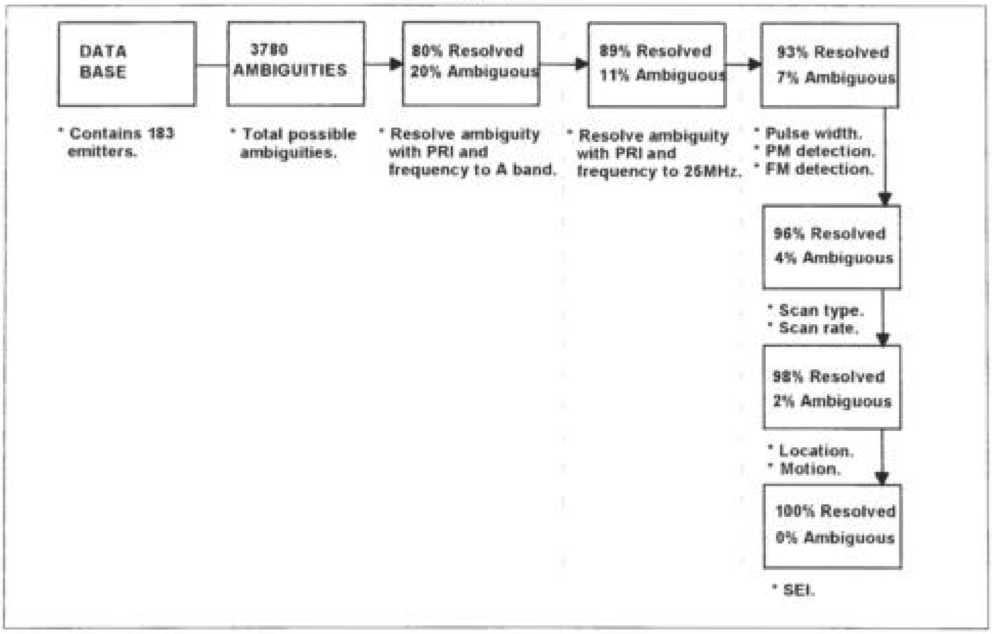


Figure 3: Test Scenarios

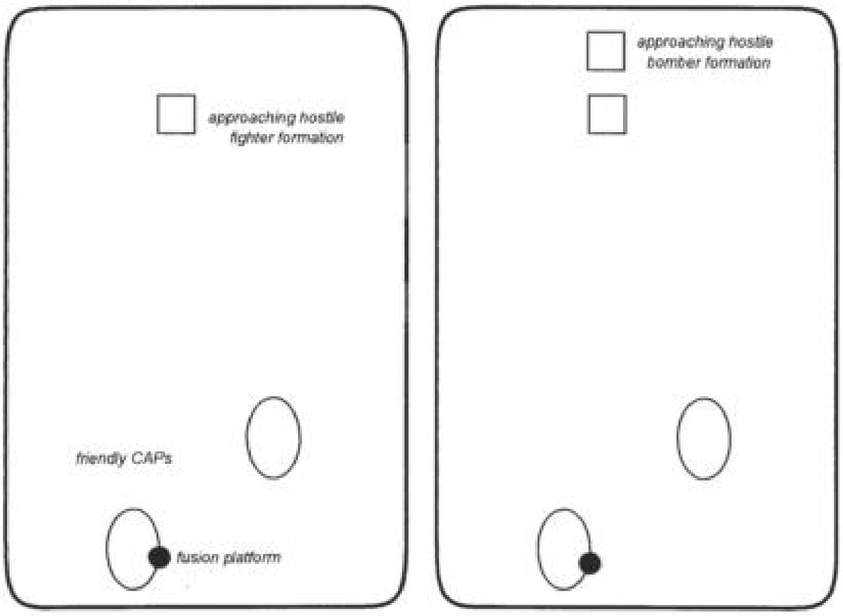
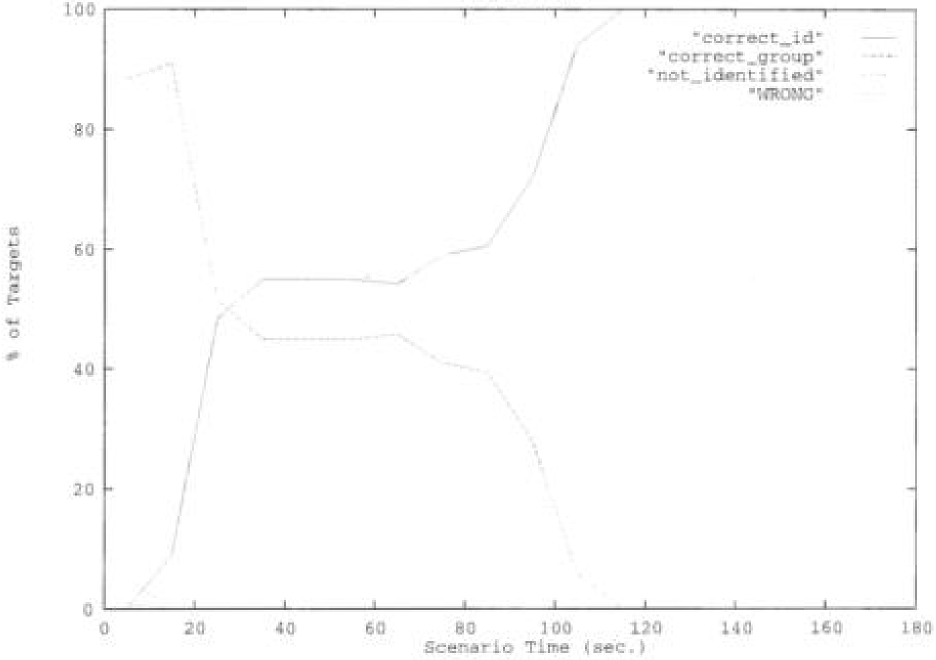


Figure 3.1



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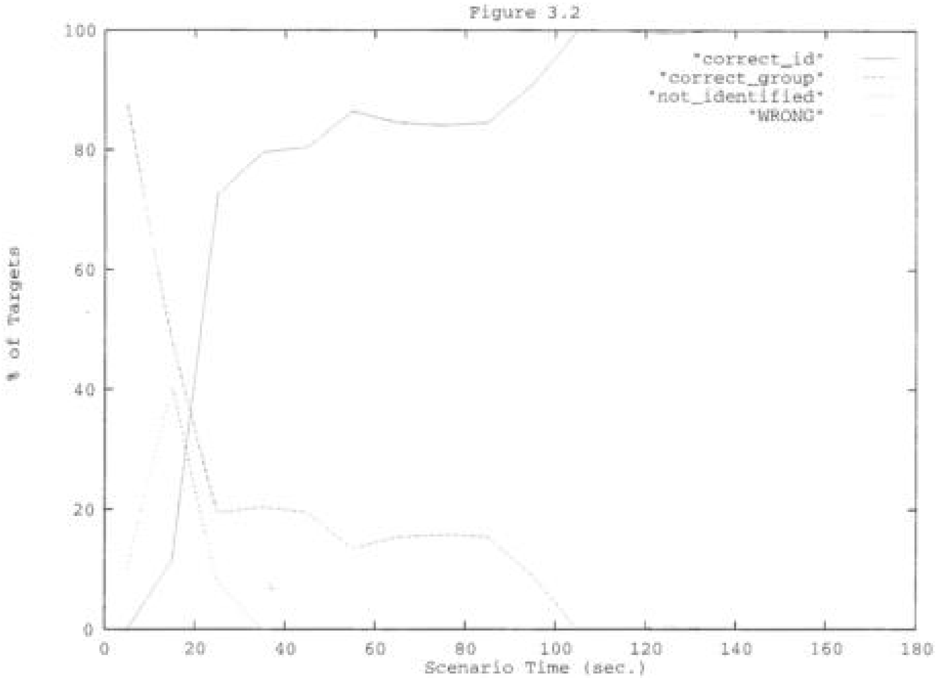

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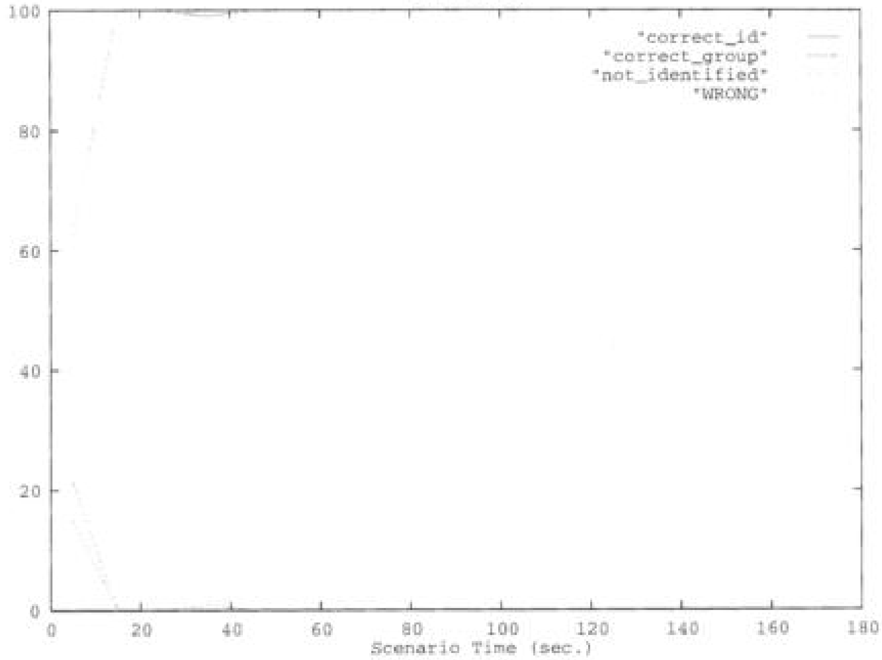

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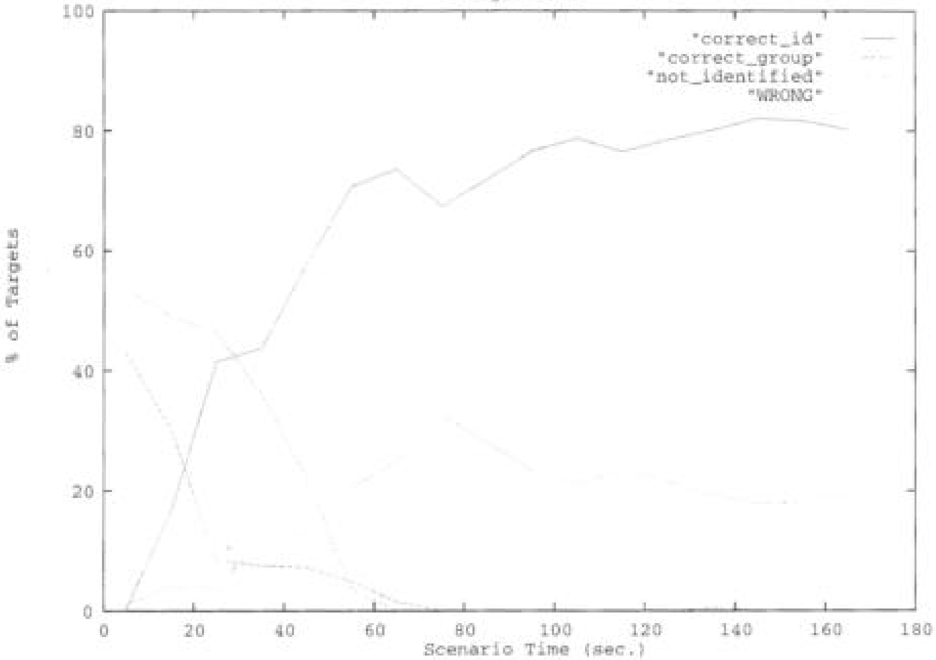


Figure 3.5

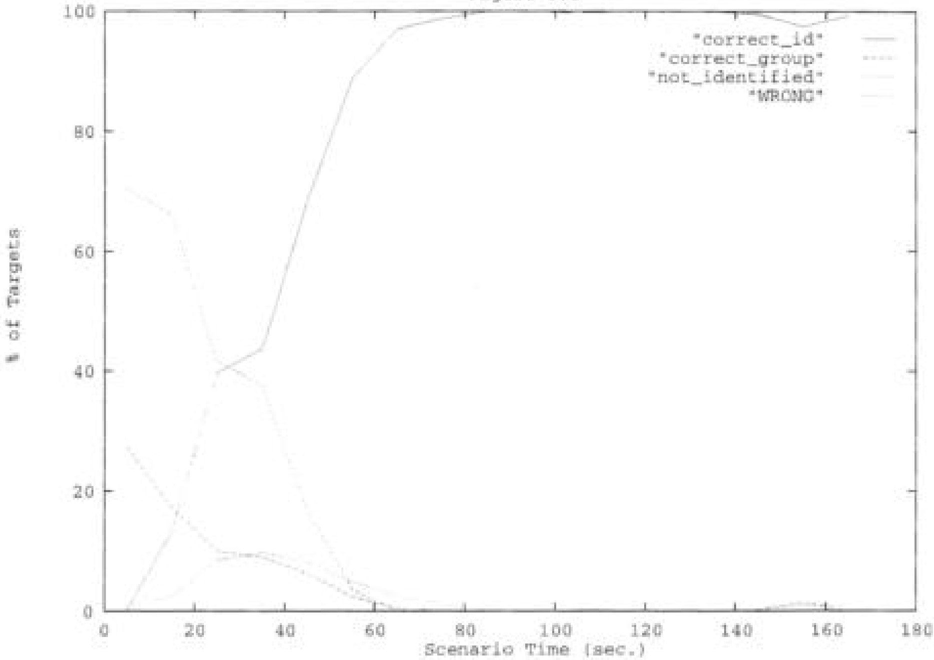
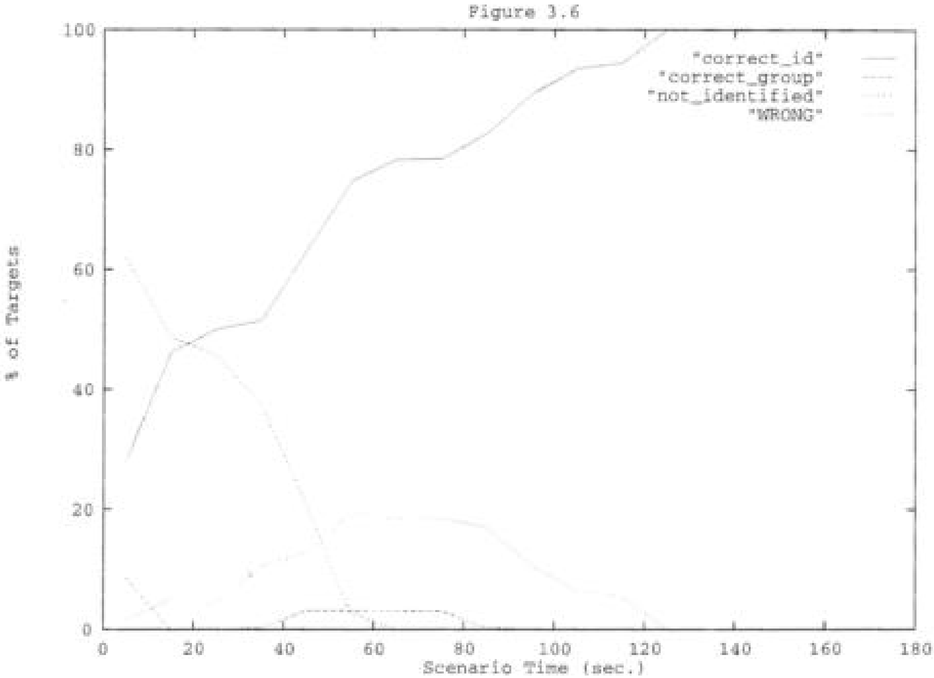


Figure 3.6



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14. Abstract

This publication reports the unclassified papers presented at a specialists' meeting held by the Sensor and Propagation Panel at its Fall 1997 meeting.

The topics covered included:

— Applications of multiple sensors and data fusion

— Data fusion techniques and methods

— Sensor data networks and management techniques

— Validation studies, experiments, technologies.