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 1 OF 2

A thesis submitted in partial fulfilment for the requirements for the degree of
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School of Computing, Engineering and Physical Sciences

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ABSTRACT

This thesis addresses the key challenge of improving multi-threat RF environment simulator capability and fidelity to the level where most, if not all electronic warfare receiver performance could be adequately proven on ground-based test facilities rather than by expensive and difficult to repeat flight trials. For over 25 years the author has investigated his claim that this could be achieved, enabled by suitably enhanced RF threat simulators. The author's technology development and management leadership has significantly influenced high-fidelity, multi-threat RF emitter scenario simulation capabilities during this period.

The published works and this thesis demonstrate this claim to be justified via the many simulator technology developments he has managed to fruition, those many potential enhancements he has identified, and four further research directions he has proposed. Many prior limitations have been overcome by technological developments and the author considers it likely that most remaining ones will be overcome within the next decade, leaving only those receiver performance verification tests that can only be done in flight to be done via flight test.

When taken as a whole, the 12 published works represent a significant contribution to the body of aerospace knowledge across the domains of survivability, electronic warfare systems and their test and evaluation, and radio/radar frequency threat simulation. Synthesis of those works demonstrates a coherent theme that links improved multi-threat RF environment simulation capability to more affordable, shorter and less risky receiver development programmes, which thereby also offers improved air platform survivability. The key importance of defence sector affordability is also recognised via development, described in the thesis, of a technology prioritisation assessment method to aid decision making on threat simulation fidelity enhancements.

Originality is also demonstrated in the works' and this thesis' development of public release reference material in the sensitive topic area of electronic warfare and test and evaluation, for the education of novices of graduate level and upwards, for the advisement of technical professionals, experienced testers and academics, and for the guidance of programme managers.

TABLE OF CONTENTS

VOLUME 1

TABLE OF FIGURES

TABLE OF TABLES

LIST OF PUBLISHED WORKS ('THE WORKS')

The following publications have been submitted as part of the PhD application.

1. Welch, M.J. and **Pywell**, M., 2012. *Electronic Warfare Test and Evaluation.* NATO RTO-AG-300 Vol.28, Issue 1. [online] Available at: <http://www.cso.nato.int/abstracts.aspx> [Accessed 12 September 2013].

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10. Wyman, G., Murphy, T.J. and **Pywell**, M., 1999. *Enhanced Survivability through Improved Emitter Location Techniques.* NATO RTO (SCIP) Symposium on 'Flight in a Hostile Environment', October. [Maryland, USA] RTO-MP-47; AC/323(SCI)TP/22. [online] Available through: NATO website: <http://www.cso.nato.int/pubs/rdp.asp?RDP=RTO-MP-047> [Accessed 16 September 2013].

11. **Pywell**, M., 1997. *EW threat simulators and environment modelling*. Journal of Electronic Defense. November, pp.45-61. Dedham, MA: Horizon House/Microwave.

12. Noonan, C.A. and **Pywell**, M., 1997. *Aircraft Sensor Data Fusion: An Improved Process and the Impact of ESM Enhancements.* NATO AGARD Sensor and Propagation Panel Symp. On 'Multi-Sensor Systems and Data Fusion for Telecommunications, Remote Sensing and Radar', September [Lisbon, Portugal] AGARD-CP-595.

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Firstly I would like to thank my Director of Studies, Professor Lik-Kwan Shark, for his kind guidance during my PhD journey.

I acknowledge the support of BAE Systems. I am fortunate to have had such an interesting and challenging career, to have travelled so far and wide, and to have worked over 38 years with so many like-minded technology enthusiasts. I thank all those with whom I've worked, especially Mitch Midgley-Davies, who has trodden some of the RF threat simulator development path with me.

Special thanks go to co-authors of my peer-reviewed publications – without their excellent contributions I wouldn't be doing this PhD. Likewise to publishers for permission to include the publications in this thesis: Institution of Engineering and Technology, John Wiley and Sons Ltd., the Association of Old Crows, the Royal Aeronautical Society and NATO's Science and Technology Organization, Collaboration Support Office.

I would also like to thank the Chairmen of NATO Research and Technology and Industrial Advisory Group studies I have participated in since 1998. Under their leadership I have had the pleasure of working with some of the finest minds in Electronic Warfare – simultaneously stimulating, stretching and enjoyable.

These acknowledgements would not be complete without mention of my RF threat simulator colleagues, too many to name individually, in Northrop Grumman Amherst Systems Inc., of Buffalo, USA. Throughout 22 years I have found them always receptive to new ideas and rising to technology challenges.

My thanks also go to Dr. Bob Andrews, of EW Simulation Technology Ltd., the UK's main RF threat simulator manufacturer. He kindly reviewed the key peer-reviewed publication and has been the source of much useful information.

Thanks also go to UCLAN Graduate Research Support Office, especially Clare Altham and Fiona Mair, for their help and timely responses to my many and varied questions on the PhD (by Published Works) process.

If I've missed anyone - my apologies and grateful thanks.

Last, but not least, I would like to thank my darling wife of 33 years, Julie, for – well - everything! Without her love and encouragement this would not have come to pass. To my daughter Samantha, likewise go thanks for morale boosting monthly progress review meetings with excellent cappucinos.

DEDICATION

This thesis is dedicated to the memory of my late parents.

They realised the importance of family and

of giving their sons the best start in life

– a good education.

Requiescant in Pace.

LIST OF ABBREVIATIONS

AAA	Anti-Aircraft Artillery
AAG	Air-to-Air Guns
AAM	Air-to-Air Missile
AAP	Allied Administrative Publication
AATF	Aircraft Anechoic Test Facility
ADRS	Advanced Dynamic Radio frequency Simulator
ADS	Air Defence System
AFB	Air Force Base
AFEWS	[US] Air Force EW Evaluation Simulator
AFFTC	[US] Air Force Flight Test Center
AFI	[US] Air Force Instruction
AGARD	[NATO] Advanced Guidance for Alliance Research and Development
AI	Avionic Integration
a.k.a.	Also known as
AMES	Advanced Multiple Emitter Simulator
AN/APR	US nomenclature for Airborne Radar Receivers
AOA	Angle-of-Arrival, Analysis of Alternatives
ARM	Anti-Radiation Missile
ASIL	Advanced System Integration Laboratory, Patuxtent River, MD
AT&E	Acceptance T&E
BAF	Benefield Anechoic Facility, Edwards AFB, California
BDA	Battle Damage Avoidance
BDR	Battle Damage Repair
BDT	Battle Damage Tolerance
CEESIM	Combat Electromagnetic Environment Simulator
CHAFF	[Originally] Chopped Aluminium Foil
CIJ	Close In Jamming/Jammer
CM	Countermeasures
CNN	Cable Network News
COMINT	Communications Intelligence
CONOPS	Concepts Of Operation
COTS	Commercial Off The Shelf
CW	Continuous Wave

LIST OF ABBREVIATIONS (continued)

DA	Defensive Aids
D&C	Display(s) and Control(s)
D&D	Design and Development
DAS, DASS	DA Suite/System, DA Sub-System
DE	Directed Energy
DEAD	Destruction of Enemy Air Defences
DEW	DE Weapon
DEWDB	[UK] Defence EW Data Base
DF	Direction Finding
DGEN	Digital Generation
DOA	Direction of Arrival
DoD	[US] Department of Defense
DoF	Degrees of Freedom
DOT&E	Director OT&E
DSTL	[UK] Defence Science and Technology Laboratory
DT&E	Developmental Test and Evaluation
DTO	Digitally Tuned Oscillator
EA	Electronic Attack
EC	Electronic Combat
ECM	Electronic Countermeasures
ECCM	Electronic Counter Countermeasures
ECR	Electronic Combat Range, California
EGA	Environment Generation and Analysis
EL	Emitter Location
ELINT	Electronic Intelligence
EM	Electromagnetic(s)
EMC	Electromagnetic Compatibility
EMCON	Emission Control
EMP	Electromagnetic Pulse
EO	Electro-Optical
EOB	Electronic Order of Battle
EP, EPM	Electronic Protection, EP Measures
ES	Electronic Support (a.k.a. EW Support)
ESJ	Escort Jamming/Jammer
ESM	Electronic Support Measures, EW Support Measures
EW	Electronic Warfare
EWEG	EW Environment Generator
EWST	EW Simulation Technology Ltd.
EWTF	EW Test Facility

LIST OF ABBREVIATIONS (continued)

EWTES	EW Threat Environment Simulation
FC	Fire Control
FDOA	Frequency Difference Of Arrival
FLO	Frequency-Locked Oscillator
GUI	Graphical User Interface
HITL	Hardware-In-The-Loop
HSS	High Speed Synthesiser
ID	Identification, Identify
IEE	[UK] Institution of Electrical Engineers (now Institution of Engineering and Technology, IET)
IEEE	[US] Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IFM	Instantaneous Frequency Measurement
INTEL	Intelligence
IR	Infra-Red
IRS	IR Signature
IST	[STO] Information Systems Technology
ISTF	Installed System Test Facility
IT	Information Technology
ITEA	Integrated Test, Evaluation and Acceptance; International T&E Association
JED	Journal of Electronic Defense
J-PRIMES	Joint-Prefight Integration of Munitions and Electronic Systems
kPPS	Kilo-Pulses Per Second
LO	Low Observability
LOB	Line(s) Of Bearing
MAA	Monitor And Analysis
MAEWTF	Multi-national Aircrew EW Training Facility
MARO	Months After Receipt of Order
M&S	Modelling and Simulation
MD	Mission Data
MDD	Mission-Dependent Data

LIST OF ABBREVIATIONS (continued)

MDS	Minimum Discernable Signal
MF	Measurement Facilities
MG	Missile Guidance
MoD	Ministry of Defence
MOP	Modulation On Pulse
MOTS	Modified Off The Shelf
MPPS	Mega-Pulses Per Second
MRA4	Maritime Reconnaissance and Attack Mk.4
mtbf	Mean Time Between Failures
N/A	Not Applicable
NATO	North Atlantic Treaty Organization
NAVAIR	[US] Naval Air Systems Command
NAWC	[US] Naval Air Warfare Center
NBC	Nuclear, Biological and Chemical
NDIA	[US] National Defense Industrial Association
NEC	Network Enabled Capability
NEDB	NATO Emitter Database
NEWEG	Next-generation EW Environment Generator
NIAG	NATO Industrial Advisory Group
OAR	Open Air Range
ORBAT	Order of Battle
OT&E	Operational Test and Evaluation
PD	Pulse Doppler
PIN	P-type – Intrinsic region – N-type semiconductor
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PW	Pulse Width
R&D	Research and Development
RAF	Royal Air Force
RAM	Radar Absorbent Material
R&T	Research and Technology
RCS	Radar Cross Section
RF	Radio/Radar Frequency
RFEG	RF Emitter Generator
RFGEN	RF Generation
RMS	[ECM] Response Measurement System

LIST OF ABBREVIATIONS (continued)

r.m.s.	Root Mean Square
RTO	[NATO] Research and Technology Organisation (re-named July 2012 to Science and Technology Organisation – STO)
RWR	Radar Warning Receiver
Rx	Receiver
SA	Situation Awareness
SAG	Scenario Advisory Group
SAM	Surface-to-Air Missile
SAS	[NATO STO] Simulation, Analysis and Studies panel
SCI	[NATO STO] Systems, Concepts and Integration panel
SEAD	Suppression of Enemy Air Defences
SEI, SEID	Specific Emitter Identification
SI	System Integration
SIGINT	Signals Intelligence
SIJ	Stand In Jamming/Jammer
SIL	Systems Integration Laboratory
SIMON	Signal Monitoring System
SJ	Support Jamming/Jammer
SMS	Signal Measurement System
SNR	Signal-to-Noise Ratio
SOJ	Stand-Off Jamming, Jammer
SPJ	Self-Protection Jamming, Jammer
SPP	[NATO STO] Sensors and Propagation Panel
SS	Sub-System
SSC	Software System Control
STO	[NATO] Science and Technology Organisation
SUT	System Under Test
T&E	Test and Evaluation
TDOA	Time Difference Of Arrival
TEWES	Tactical EW Environment Simulator
TMO	Target Management Office
TOTS	Tailored Off The Shelf
TRL	Technology Readiness Level
TT	Target Tracking
TTP	Tactics, Techniques and Procedures
TV	Television

LIST OF ABBREVIATIONS (continued)

UAV	Unmanned Aerospace Vehicle
UCLAN	University of Central Lancashire
UV	Ultra-Violet
UK	United Kingdom
US	United States
USA	United States of America
USAF	United States Air Force
V&V	Verification and Validation
VCO	Voltage-Controlled Oscillator
VfM	Value for Money
WARM	Wartime Reserve Modes
YIG	Yttrium Iron Garnet
3-D	Three Dimensional

LIST OF SYMBOLS

P_H	Probability of Hit
P_K	Probability of Kill
$P_K RF$	P_K Reduction Factor

Chapter 1

INTRODUCTION

1 INTRODUCTION

1.1 BACKGROUND

1.1.1 Setting the scene

This thesis covers the development of high-fidelity test technology for comprehensive evaluation of Electronic Warfare (EW) systems in multi-threat environments. It explores a central thread in the ideas and publications generated by my 30 years of critical investigation, evaluation and writing on the topics of air platform survivability, EW systems and their design and development, EW Test and Evaluation (T&E), and Radar/Radio Frequency (RF) threat simulation utilised for that T&E in the laboratory and anechoic chamber test environments. This central thread, or coherent theme, that runs through the peer-reviewed Published Works ('**the Works**'), when taken as a whole, is evidenced in **the Works** in Volume 2. The theme is developed in this thesis via synthesis of **the Works**.

1.1.2 Development path – research and investigations

During the above three decades I went first from being a senior avionics test engineer, systems integration testing EW and other avionic systems in the laboratory and on aircraft ground trials, additionally to a microwave and electromagnetics researcher and group leader, thence also to be my Division's EW Technology Programme Manager.

Throughout these and following years as EW Systems Specialist and then EW Technologist (Subject Matter Expert), my interest in and knowledge of the RF threat simulation topic grew. My area of particular expertise was and remains the development of threat simulator specifications and identification and resolution of simulation fidelity and other issues pertaining to their essential use in the development testing and in-service support of RF EW receiver systems.

Over the last 22 years I have led specification of 12 major RF threat simulators acquired by my Division for development and in-service support of the Eurofighter Typhoon's Defensive Aids Sub-System (DASS) and Nimrod MRA4's EW and Defensive Aids Suite (DAS). I have also been Engineering Manager (last seven years) and Project Manager (last five years) for EW Rig Support Equipment for Typhoon DASS. A supporting letter is provided at Appendix A.

For 14 years I have also represented the UK and my company on EW studies and investigations conducted under the auspices of the North Atlantic Treaty Organization (NATO) Research and Technology Organization[1] (RTO) and Industrial Advisory Group (NIAG), see Table 1-1.

NATO study	Title[2]	Role
RTO Systems, Concepts and Integration (SCI) panel Task SCI-203	Update of NATO's EW Test and Evaluation Handbook (Welch and **Pywell**, 2012).	Dstl-appointed UK co-author (US lead co-author).
RTO Simulation, Analysis and Studies (SAS) panel study SAS-064	Update of Requirements and Options for Future NATO Airborne EW Capabilities. (Keppler, 2008; North Atlantic Treaty Organization, 2010).	Sole UK Industry delegate and final report editorial team member.
NIAG Study Group 105	Self-protection interoperability (Flare-Chaff) for aircraft & UAVs. (North Atlantic Treaty Organization, 2007)	Team 1 ('System') member & final report editorial team leader
NIAG Study Group 79	Emitter Location and Data Links to facilitate Suppression of Enemy Air Defence (SEAD). (North Atlantic Treaty Organization, 2006)	Member of Teams 1 (Architectures & Scenarios) & 2 (Geo-location) and final report editorial team.
NIAG Study Group 66	Future Electronic Support System – Digital Solution (originally entitled 'Next Generation Digital Receiver'). (North Atlantic Treaty Organization, 2001)	1 of 2 UK Industry delegates. Member of Teams 1 (System) & 2 (Receiver).
RTO Study SAS-011	Requirements and Options for Future NATO EW Capabilities. (North Atlantic Treaty Organization, 2002)	Sole UK Industry delegate.

Table 1-1: NATO studies and investigations

Commendations were received from the Chairmen of above activities and one for the most important study, SAS-064, is provided at Appendix A. I was also nominated in 2013 as a prestigious BAE SYSTEMS Engineering Fellow.

Figure 1-1 is a chronology of my three decades of EW and RF threat simulator investigations. It also shows the timeline of relevant publications, including **the Works**, and (external to my company) presentations excluding those identified in section 1.1.4. It demonstrates my long-term involvement in research pertaining to the topic of this thesis and provides an indication of my contribution to knowledge in the survivability, electromagnetics, EW T&E and RF threat simulation domains over an extended period of time.

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[1] RTO has, since 1 July 2012, been re-named Science and Technology Organisation (STO).
[2] RTO reports are available, for those with clearance, via http://www.cso.int/abstracts.aspx

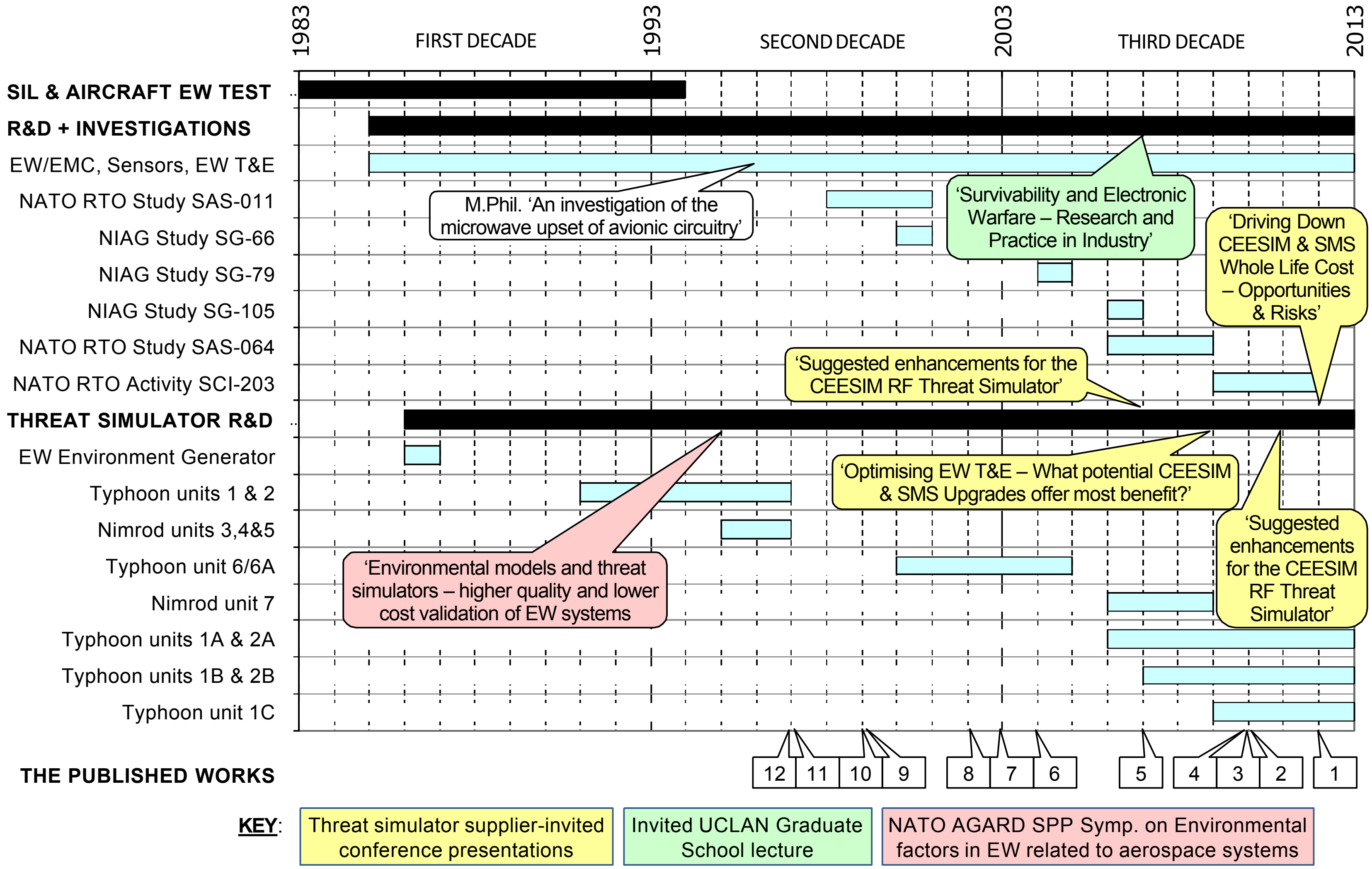

Figure 1-1: Chronology of EW T&E, R&D and RF threat simulator activities

1.2 AIMS, CONSTRAINTS AND LIMITATIONS

The aims are to:

- produce a thesis covering the development of high-fidelity test technology for comprehensive performance evaluation of RF EW systems in multi-threat environments. This thesis will encapsulate the results of this author's three decades of critical investigation and evaluation of a number of subordinate elements of air platform survivability, as evidenced by **the Works**.
- provide a critical appraisal of **the Works** and this author's related activities, and to demonstrate through this appraisal that, when taken as a body of work, **the Works** make a significant and coherent contribution to knowledge.

Some security and proprietary constraints and limitations necessarily apply to material that can be presented in this unclassified thesis. Discussion of a number of topics are thus limited to that which is open press ('public release'), that which is already contained within **the Works**, and that which has been cleared for use herein. These topics are non-exhaustively listed below.

- The survivability-relevant, but nationally sensitive topics of EW, Directed Energy Weapons (DEW), Radar Cross-Section (RCS) and Infra-Red Signatures (IRS).
- Details of threat systems and capabilities, and details of tactics and countermeasures used against them.
- RF EW receivers and consequently threat simulators operate in the same technical parameter space, as all operate generally with the same RF threat environment. No requirement or numeric herein is intended to be associated with any specific System Under Test (SUT), platform or programme.
- Emitter databases, which are essential to SUT and simulator operation but whose content is nationally sensitive.
- Electronic Intelligence (ELINT) receivers, which are, like the other EW RF receivers discussed in this thesis, tested using RF threat simulators.

It is considered that sufficient information is presented to demonstrate the required contribution to knowledge. As appropriate, statements are made to indicate the nature and scope of this author's underpinning investigations.

1.3 THE THESIS

1.3.1 Coherent theme

RF threat simulator technology developments could enable all EW RF receiver performance to be confirmed via testing on ground-based facilities rather than by expensive flight trials, since many prior fidelity limitations on multi-emitter scenario generation have been and are being overcome. Although affordability constraints will limit the eventual outcome, robust cost-benefit consideration and management of individual developments will enable an optimum level of RF threat simulator capability, however the need for some residual flight testing is likely to remain.

Survivability is essential for military platforms, to assure military success in order to meet national government policy and/or strategy. EW systems are key to survival for military air, sea and land platforms. EW is defined in North Atlantic Treaty Organization (2013a), as adopted by the United Kingdom (Great Britain. Ministry of Defence, 2011) as:

> *"Military action that exploits electromagnetic energy to provide situational awareness and achieve offensive and defensive effects." (North Atlantic Treaty Organization, 2013a, pp.2-E-2 and 2-E-3).*

RF EW systems are an essential element of platform DAS and are especially pertinent to air platforms. The general construct of an air platform's DAS and its EW components is discussed in Chapter 2. Airborne RF EW receiver systems are key DAS components and are essential to threat and Situation Awareness (SA), and consequently to air platform and aircrew survival when in hostile airspace. To assure adequacy of these receiver systems under combat conditions, exhaustive T&E is required with appropriately high-fidelity simulated RF threat multi-emitter scenarios.

A key thematic element is the improvement of RF EW T&E capabilities, in particular that of RF threat simulators, to underpin the above adequacy assurance. The primary theme*, i.e.* focus of the PhD, is that developing threat emitter simulation technology from single-emitter-at-a-time capability to truly multi-emitter scenario capability has been and continues to be a key driver for being able to do more and higher quality T&E on the ground (laboratory and anechoic chamber) than previously, thus reducing the need for flight test and reducing overall programme cost, risk and timescales.

In this thesis I will identify the research progression in the selected technological domain, describe the development of the coherent theme via synthesis of **the Works** and identify potential future research directions. The thesis will also demonstrate the development of my own understanding of the subject domain as I progressed from an individual, academically-detailed researcher through to an investigator/research manager and thence EW subject matter expert participating in, influencing and directing international research.

1.3.2 Relationship of the Works to the focus of the PhD

The relationship of **the Works** to the focus of the PhD and to each other is indicated in Table 1-2. They are substantially different in focus and content, although there is some thematic and material repetition between some of them. Each of **the Works** is synthesised across relevant chapters of this thesis.

Title of Published Work	Year	Survivability	EW/DAS	EW Receivers	Threat Location & Identity	T&E capabilities and facilities	RF threat simulation	RF emitter scenario fidelity
Electronic Warfare Test and Evaluation	2012	Y	Y	Y	Y	Y	Y	Y
Improved test capabilities for cost-effective performance evaluation of airborne EW systems	2010	Y	Y	Y	Y	Y	Y	Y
Electronic Warfare and Defensive Aids Systems Design and Development	2010	Y	Y	Y	N	Y	Y	Y
Design aspects of Aircraft Vulnerability	2010	Y	Y	N	N	Y	N	N
Developments in RF Threat Simulator Technology – Approaching the Affordable Fidelity Limit	2007	Y	Y	N	Y	Y	Y	Y
A Question of Survival – Military Aircraft vs. the Electromagnetic Environment	2004	Y	Y	Y	Y	Y	Y	N
Military Aircraft combat the Electromagnetic Environment	2003	Y	Y	Y	Y	Y	Y	N
Survivability – A Reward for Integrated Thinking	2002	Y	N	N	N	Y	N	N
The new Enigma – Increased Survivability with Reduced Cost?	1999	Y	Y	Y	Y	N	N	N
Enhanced Survivability through Improved Emitter Location Techniques	1999	Y	Y	Y	Y	N	N	N
EW threat simulators and environment modelling	1997	Y	Y	Y	Y	Y	Y	Y
Aircraft Sensor Data Fusion: An Improved Process and the Impact of ESM[3] Enhancements	1997	Y	Y	Y	Y	N	N	N

Table 1-2: Relationship of the Works to the PhD focus and to each other

[3] Electronic Support Measures, a type of RF EW receiver, also known as EW Support Measures, which is discussed in section 2.3.

1.3.3 Literature searches

This author has conducted repeated literature searches during the last three decades in the survivability, EW systems, EW T&E and RF threat simulation topic areas. **The Works** alone contain a total of 203 references from 1978 to 2012. They thus already represent the outcome of an extended and extensive literature review. The prior reviews indicated a dearth of literature on EW T&E of RF EW receiver systems in the highly specialised area of RF threat simulation of multi-emitter scenarios.

Of the 203 references, those of direct relevance have been used across the thesis chapters. These have been augmented by 97 new or more modern references discovered during 'refresher' literature searching conducted, yielding a total number of 151 references, 70% of which are from the last decade.

Only three references, covering the 2011-instigated US Next Generation EW Environment Generator (NEWEG) project and which are discussed in chapter 5, are considered major in the domain of multi-emitter RF threat simulation. This underpins the view that **the Works** are current, state-of-the-art and at the forefront of technology.

For clarity, in-text referencing of **the Works** is highlighted in bold text.

1.3.4 Thesis organisation

Earlier in this chapter the background, reason and importance to survivability of adequately validated RF EW systems on military air platform is introduced.

Chapter 2 provides definitions of survivability and its constituent elements, of which EW is one, and clarifies subtle differences between terminologies used. It explains the functions of EW systems, in particular RF receiver ones, and explains their contribution to air platform and aircrew survivability, and to mission success.

Chapter 3 discusses the evaluation of RF EW systems. The traditional approach to EW T&E of RF receiver systems is described and performance verification methods and locations are outlined. Three decades of EW T&E process developments are described and the key evaluation parameters for EW receiver systems, which drive threat simulator specifications, are highlighted.

Chapter 4 introduces RF threat simulators, explains their prominent position in the EW T&E armoury and outlines the likewise importance of the complementary EW T&E equipment, Electronic Countermeasure (ECM) Response Measurement Systems (RMS). Subtle terminology differences between the terms 'simulation' and 'emulation' are discussed. Threat simulator origins are described, from the earliest and simplest laboratory test configurations to the latest, highly complex threat simulators.

Chapter 5 expands on the development and utility of threat simulators for generating multi-emitter threat scenarios at RF for the T&E of EW receiver systems. Development of RF threat scenarios for EW T&E is described. Simulator technology development methodology is described and this author's contribution to driving out key development requirements is highlighted. Development of an affordability-driven simulator technology prioritisation assessment method is also described and an exposition of two decades of simulator technology development is provided. This chapter also includes a discussion of simulation fidelity and the related question '*What is enough?*'.

Chapter 6 presents conclusions, states the contribution to knowledge and provides suggestions for further research.

1.4 OVERALL CONTRIBUTION TO THE FIELD

This author's overall contribution to the field is indicated in this section.

This author's contribution to the 12 peer-reviewed publications are summarised in Table 1-3, which shows that, where he is not the sole author, he has made significant contributions to **the Works**

No. of publications	Contribution	Number of authors
5	100%	1
1	80%	2
1	70%	4
2	50% of each publication	2 authors/publication
1	40%	2
1	33.3%	3
1	20%	3

Table 1-3: Contributions to the Works

Table 1-4 identifies invited presentations on topics relating to RF threat simulator and ECM RMS enhancements, and affordability trade-offs. The inviter was Northrop Grumman, Amherst Systems Inc., manufacturer of the world's most prolific high-end RF threat simulator, the Combat Electromagnetic Environment Simulator (CEESIM), and the Signal Measurement System (SMS), a type of ECM RMS. Appendix A contains a supporting letter from that company's Site Director. The un-published 2011 presentation, on affordability prioritisation of potential simulator and RMS technology upgrades, is particularly relevant and is discussed in detail in chapter 5. In 2012, this author presented at and led a discussion session on affordability and cost-reduction aspects of threat simulators and ECM RMS.

Driving down CEESIM and SMS Whole Life Cost – opportunities and risks [Presentation & Discussion Session co-Lead]	'Simulation Systems for the UK Community' meeting, Peterborough, UK, 21 June 2012 (Pywell, 2012).
Optimising EW Test and Evaluation – Which potential CEESIM and SMS upgrades offer most benefit?	UK CEESIM Users' Review Meeting, Peterborough, UK, 8-9 June 2011 (Pywell and Midgley-Davies, 2011).
CEESIM and SMS – Where to Next? An Industry view of potentially worthwhile developments	UK CEESIM Users' Conference, Peterborough, 3-4 June 2009.
Suggested further development of the CEESIM RF threat simulator	UK CEESIM Users' Conference, Peterborough, UK, 15 March, 2007.

Table 1-4: Presentations invited by leading RF threat simulator supplier

In addition to those presentations in Table 1-4, other relevant EW and T&E presentations have been given in recent years:

- Pywell, M. and Midgley-Davies, M. 'Improved Test Capabilities for Cost-effective Performance Evaluation of Airborne Electronic Warfare Systems'. Confederation of European Aerospace Societies 2009 – European Air and Space Conference, Manchester, U.K. 26-9 October. (Pywell and Midgley-Davies, 2009).
- Pywell, M. and Midgley-Davies, M. 'Optimising Electronic Warfare Test and Evaluation'. Lecture to the Lancashire and Cumbria Network of the Institution of Engineering and Technology, Warton, UK, 2 November 2011.
- Invited presentation of updated version of 'Optimising EW T&E', presented by co-author, RAF Club, London, UK. 23 May 2012. The authors received a commendation, see Appendix A, for this presentation from the President of the UK Chapter of the Association of Old Crows[4].
- Slater, G. and Pywell, M. De-risking platform clearance of Electronic Warfare systems. 8th EW Symposium, Defence Academy of the UK, Shrivenham, UK. 5-6 December 2012 (Slater and Pywell, 2012).

Table 1-5 lists this author's EW-related patent applications. Some have classified content which cannot be divulged in this thesis. Only the Great Britain patent application number is given; most were extended to other countries.

Year	Number	Author(s)	Title
2006	GB 0622259.0	G. Wyman, F.M. Watkins, M. Pywell	Emission Control System (Sensor Management and EMCON)
2005	GB 0512720.4	M. Pywell, P. Newham	Improvements in or relating to antennas
2003	GN0319117.8	M. Pywell, G. Wyman, F.M. Watkins	Improvements in or relating to emission suppression
2000	GB0005826.3	M. Pywell, G. Wyman, T.J. Murphy	System for Detecting and Locating the Emission Source of Incoming Electromagnetic Radiation
1999	GB9924079.8	M. Pywell, G. Lyons	Radar Systems & Method (ESM/ECM-based IFF Transponder/Interrogator)
1998	GB9805158.4	M. Pywell, J. Green	Low Cost Radar Decoy
1997	GB97310092.8	R.C.N. Woolnough, M. Pywell	Adaptive Filter (Low cost Radar Warning Receiver, RWR)
1996	GB9626117.7	R.C.N. Woolnough, M. Pywell	Decoy Elements' (Laser countermeasure)

Table 1-5: Patent applications

[4] *"The Association of Old Crows (AOC) is a not-for-profit international professional association with over 13,500 members and 180+ organizations engaged in the science and practice of Electronic Warfare (EW), Information Operations (IO), and related disciplines*." (www.crows.org/). AOC has members in 47 countries with 69 chapters in 20 countries. Membership includes executives, scientists, engineers, managers, operators, academics and military personnel.

This author has also received six prestigious Bronze Chairman's Awards from his company, BAE Systems, see Table 1-6. All relate to EW activities and three pertain to RF threat simulators and ECM RMS and their technology development.

Year	Title	Category
2011	Typhoon DASS Rig Support Equipment Refresh	Supporting our Total Performance Culture
2008	Electronic Warfare Test Equipment	Transferring Best Practice
2003	ESM/ECM-based Identify Friend or Foe (patent application)	Innovation and Technology
2002	Enhanced RF Threat Simulator Technology	Innovation and Technology
2001	Towed Decoy (patent application)	Innovation and Technology
2001	EW Web Page on the Intranet	Transferring Best Practice

Table 1-6: Chairman's Awards

Chapter 2

EW AND ITS CONTRIBUTION TO AIR PLATFORM SURVIVABILITY

2 EW AND ITS CONTRIBUTION TO AIR PLATFORM SURVIVABILITY

2.1 INTRODUCTION AND DEFINITIONS

This chapter provides definitions of survivability and its constituent elements, of which EW is one, and clarifies subtle differences between terminologies used. It explains EW system functions, in particular RF receiver ones, and explains their contribution to air platform and aircrew survivability, and to mission success.

2.1.1 Importance of air platform survivability

The projection of robust air power, in the form of Armed Forces with survivable aircraft, is a key factor in winning battles, campaigns and wars. Attaining and maintaining air superiority in modern conflicts usually guarantees victory. Many conflicts since World War 2 and the ongoing international war against terrorism have under-scored the need for capable and survivable aircraft.

The importance of military air platform survivability (hereinafter referred to as 'survivability') to the military mission cannot be over-stated. It is necessary to provide the highest probability of mission success, with minimal or zero loss of own aircraft and aircrew, at minimum overall (operating plus war-fighting) life cycle cost.

2.1.2 Survivability and EW - definitions and terminologies

Survivability and EW do not have world-wide agreed definitions and terminologies and a number of definitions and terminologies exist. Some vary internationally and others intra-nationally, *i.e.* between and within military/defence/industrial agencies within a country. As a result, throughout **the Works** and in the NATO and other research studies this author has participated in, it has been necessary to clearly define specific terms where ambiguity, impreciseness or confusion would otherwise have resulted. Over the last decade and particularly in the last few years there has been significant move toward international standardisation of definitions and terminology.

Examples, mostly referenced **in the Works** include:

- Glossary of Defense Acquisition Acronyms and Terms (Defense Acquisition University, 2005).
- NATO Glossary of Terms and Definitions, Allied Air Publication 6 (North Atlantic Treaty Organization, 2013a).
- NATO Glossary of abbreviations used in NATO documents and publications, Allied Air Publication 15 (North Atlantic Treaty Organization, 2013b).
- Common Terms used in Modelling and Simulation (M&S) (Great Britain. Ministry of Defence, 2011a).
- UK Supplement to the NATO Terminology Database (Great Britain. Ministry of Defence, 2011b)

It is not necessary to repeat all the definitions from the Works and the above studies here as, where necessary, they are called out as required in later thesis sections. The more important definitions and terminologies, of survivability and EW, which is also known in the USA as Electronic Combat (EC), are provided in this section.

Air combat survivability, at a discipline level, can be defined as the capability of an aircraft to avoid or withstand (sustain) a man-made hostile environment (Ball, 2003; Ball and Atkinson, 2005). More generally, survivability can also be defined as a measure of an aircraft's tolerance and persistence within a given environment, recognising that environment has war-time, man-made threat component and peace-time, safety-related components (United States. Department of Defense, 1997; **Pywell** *et al.,* 1999).

This man-made hostile, or war-time environment comprises Surface-to-Air Missiles (SAMs), Air-to-Air Missiles (AAMs), Anti-Aircraft Artillery (AAA), Air-to-Air Guns (AAG) and DEW, which includes nuclear and non-nuclear ElectroMagnetic Pulse (EMP). This is distinct from the peace-time threat environment, which includes lightning strike, ElectroMagnetic Compatibility (EMC), electro-static discharge, cosmic radiation and bird strike. Of note is that, during combat, war- and peace-time threats can exist, although generally the hazard to platform and aircrew survival is much higher from the former. For example, during combat an aircraft is much more likely to be shot down than lost to lightning strike (**Pywell**, 2004).

The definition of EW has, over the last decade, neared international consensus:

> *"Any action involving the use of electromagnetic and directed energy to control and protect the own usage of the electromagnetic spectrum or to attack an adversary and deny his access." (**Pywell**, 2010, p.4632).*

> *"Military action that exploits electromagnetic energy to provide situational awareness and achieve offensive and defensive effects." (North Atlantic Treaty Organization, 2013a, pp.2-E-2 and 2-E-3).*

Table 2-1 depicts the inter-relationship between survivability terminologies.

Ball (2003), United States. Department of Defense (1997)	**Pywell** et al. (1999), MacDiarmid, Alonze and **Pywell** (2002)	**Pywell** (2003)	Wickes[5] (2005, cited in Law, 2011, p.8)
Susceptibility	Battle Damage Avoidance	Pre-kill, neutralise, eliminate threat	[Not applicable]
		Avoid	Don't be there
		Evade	Don't be seen
		Counter	Don't be engaged
Vulnerability	Battle Damage Tolerance	Tolerate/Sustain damage	Don't be damaged
Recoverability	Battle Damage Repair	Repair	Don't be killed (aircrew or loss of aircraft

Table 2-1: Inter-relationship between survivability terminologies

Another view of this inter-relationship is from the perspective of survivability mechanisms: Threat Avoidance, Attack Evasion, Threat Elimination and Damage Tolerance, as discussed in **Pywell** *et al.* (1999), where survivability is decomposed under headings of Battle Damage Avoidance (BDA), Battle Damage Tolerance (BDT) and Battle Damage Repair (BDR).

A third view, in MacDiarmid, Alonze and **Pywell** (2002), considers major properties influencing survivability and major considerations influencing damage tolerance.

[5] Dr. J.B. Wickes, Chief Technologist Survivability, DSTL, UK.

All of the above views are valid and are broadly consistent with Ball (2003), with each considering survivability from a particular domain standpoint. For example Vulnerability engineers usually use BDA/BDT/BDR philosophy and terminology, whereas EW engineers would more likely use philosophies of pre-kill/avoid/evade/counter threats that utilise the EM environment, and sustain any weapon-caused damage that occurs (**Pywell**, 2004; 2010).

In every case the overall goals of survivability are the same: to maximise the probability of successfully completing the mission; to be capable of quick repair and return to the fray if damaged in battle; and to keep the aircrew as safe as possible for as much of the time as possible, if not always.

2.2 EW AND DAS – IMPROVED SURVIVAL POTENTIAL

2.2.1 Survivability components, drivers and trade-offs

Optimally affordable survivability for a specific platform type in a particular operational scenario can only be met by careful consideration of the balance between individual components of survivability (**Pywell** *et al.*, 1999; MacDiarmid, Alonze and **Pywell**, 2002; Ball, 2003; **Pywell**, 2004; Law, 2011). The overall objective is to achieve the best level of survivability commensurate with mission objectives and within whole life affordability constraints.

Figure 2-1 shows the complex relationship between survivability components and their linkage to the survivability terminologies stated in section 2.1.2.

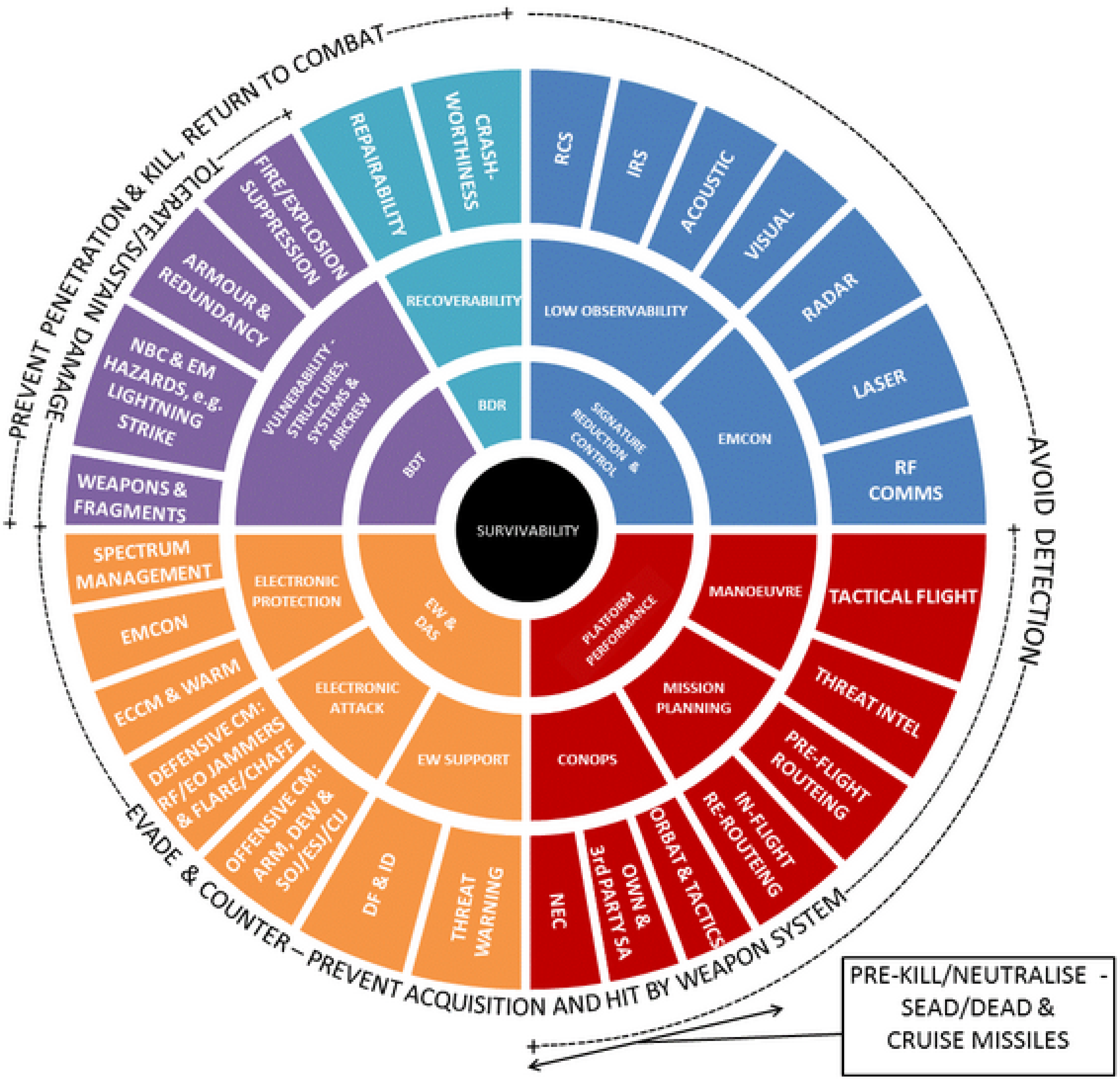

Figure 2-1: Survivability components and terminologies

Figure 2-1 shows how survivability depends on the interaction of many individual components, each of whose relative importance varies dependent upon platform role and mission. For example, Armour and Redundancy are very important for close air support, but are less so for air-to-air combat, whereas threat Direction Finding (DF), Identification (ID) and Emitter Location (EL), and Emissions Control (EMCON) are equally important to both. In reality, no single component can guarantee survival to complete the mission and, even if an optimal balance is achieved, this does not assure mission success and safe return to base.

Prior to the advent of the first stealthy aircraft types, *e.g.* B-1B 'Lancer', F-117 'Nighthawk' and B2 'Spirit', it was generally accepted that the lack of EW systems, in the form of self-protection (DAS) or support jamming[6], would significantly increase aircraft loss in combat. Stealth, also known as Low Observability (LO) and platform signatures' reduction, was seen for some time by many as negating the need for EW and DAS as it provided invisibility that allowed the platform to creep up on its target completely un-detected. It took some years for a general understanding to emerge that, whilst stealthiness reduces the range at which enemy sensors can detect a platform's approach, thus reducing the opposition's time available to activate and employ defence weapons, it does not confer invincibility on that platform. Eventually, through multi-spectral sensing (including acoustic and optical), the enemy becomes aware of the platform's ingress to the target. DAS is mission critical from this point through to successful attack prosecution and is crucial to survival until after egress from the target area. The 1999 SAM shoot-down of a F-117 aircraft in the Kosovo conflict served to underline this need for an optimal balance of survivability components and a capable and effective DAS (Gosling, 2000; Wexler, 2005; Pywell, 2006).

[6] Support Jamming comprises Stand-Off Jamming (SOJ), Escort Jamming (ESJ) and Close-In Jamming (CIJ), the latter of which is also known as Stand-In Jamming (SIJ).

The postulation that the best, or rather most affordable answer lies in such an optimal balance was considered in **Pywell** *et al.* (1999). This was, in effect, a UK position paper at the time and benefitted from the unique authors' Industry and MoD grouping, with Pywell, Hurricks and Wellings also being UK's representatives on NATO RTO Study SAS-011 (see Table 1-1), which 1998-2000 investigated requirements and options for future NATO air/sea/land EW.

Pywell *et al.* (1999) considered the enigma of how to increase aircraft survivability, to enable improved availability for operations, whilst simultaneously meeting increasingly stringent affordability levels of Defence Ministries and international competition. The enigma was complex and can be decomposed to:

- How can industry ensure its customers can procure effective but affordable aircraft when there are so many variables? Examples include imprecise and incomplete threat scenario definitions and shrinking budgets.
- Can survivability and mission performance be increased whilst fewer numbers of aircraft are being procured?
- What are dominant costs of improving survivability against threats and does improving one component offer better Value for Money (VfM) than another?

Those authors described evolution of cost control and estimating methods and the move away from 'gold-plated', all-encompassing requirements (to cover the above 'unknowns', albeit at high cost) toward fully traceable, justified and prioritised requirements. The importance of taking all costs into account when performing survivability trade-offs was emphasised – at that time operation, support and combat costs were not usually included, whereas nowadays per-aircraft and fleet whole life, or 'life cycle' costs are used in defence ministry investment appraisals. Those authors also discussed modern and future air warfare and contextualised survivability against a background of changing nature of the threat environment and evolving military requirements. A substantial part of the paper addresses survivability components and their importance to wartime operations. A number of technological options for increased damage avoidance and per-aircraft and fleet survivability improvement were proposed, some of which have subsequently come to pass, *e.g.* digital receivers and improved interoperability.

Some key survivability drivers were identified and discussed:

- Zero or 'near-zero' attrition, for increased military success probability and counter-propaganda purposes - the 'Trial by CNN' factor.
- Threat environment, probabilities of encountering threats and probabilities of them damaging or killing the aircraft and its crew.
- Reliability: a perfect threat countermeasure is useless if it fails intra-mission.
- Per-platform DAS capability and available Support Jamming.

The threat environment is particularly important. It is a significant variable over the 20+ year life time of typical military aircraft. There have been, for example, substantial changes in military environments in recent decades, from traditional warfare between major powers towards asymmetric conflicts[7], including counter-terrorist operations (Keppler, 2008; **Pywell** and Midgley-Davies, 2010).

Pywell *et al.* (1999) also provided an EW perspective of the survivability vs. cost trade-off space. The results of an earlier, internal report (Pywell, 1996a) were presented in an unclassified form, see Figure 2-2.

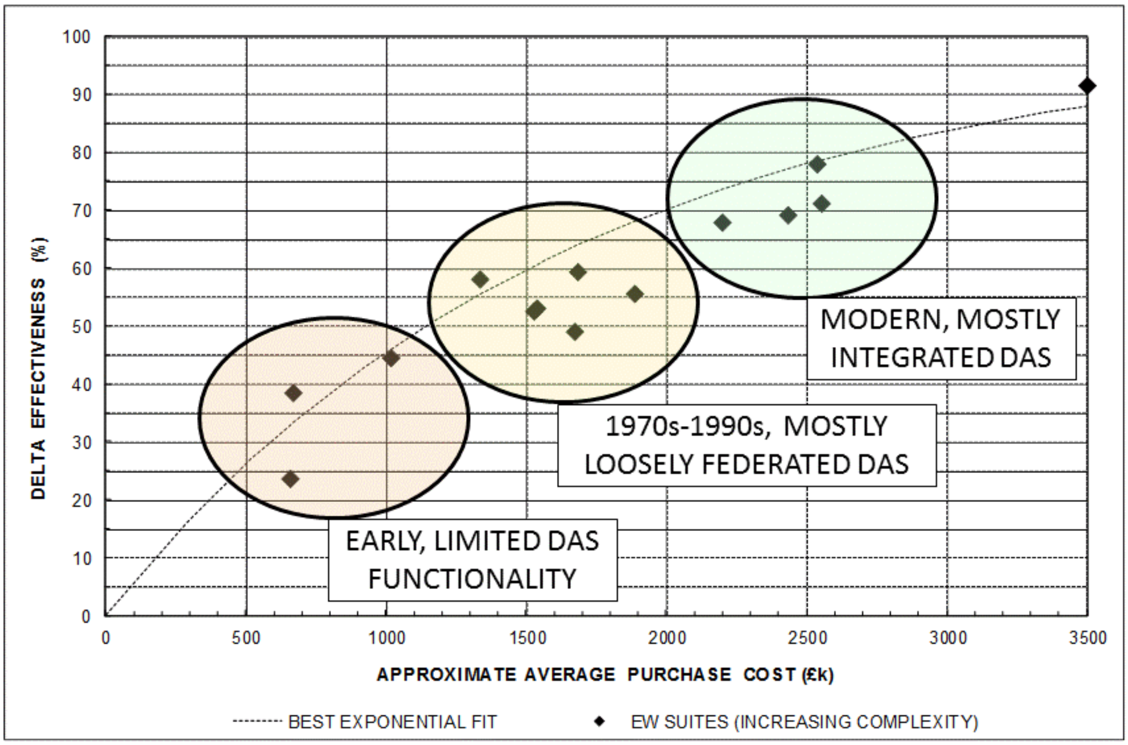

Figure 2-2: DAS content vs. indicative cost vs. increase in effectiveness

[7] "*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*." (North Atlantic Treaty Organization, 2012). Relates to insurgency and terrorism.

Figure 2-2 indicates, via coloured and labelled groupings, how better per-platform survivability can be achieved via EW by adding first functionality, then additional performance to the DAS equipment fitted to a given platform, although each improvement costs extra. Note that the 'Effectiveness' scale is relative, showing the delta increase in effectiveness against the investigated set of threat scenarios, rather than being an absolute measure of effectiveness against a specific threat in a specific scenario.

BDT and BDR improvements were also considered in **Pywell** *et al*. (1999) and a proposed improved process, integrated survivability analysis, was elaborated in comparison to the then traditional approach. Whilst of less importance to this EW-related thesis, the crucial nature of Vulnerability was recognised, given that EW equipment could not and still cannot guarantee survival against all threat types in all mission scenarios. **Pywell** and MacDiarmid (2010) expanded on this point, highlighting the need for holistic vulnerability analyses during a platform's design and development phase if optimum vulnerability is to be achieved. If it is actually possible, it is technically complex and usually very expensive to retro-fit vulnerability improvements. MacDiarmid, Alonze and **Pywell** (2002) expanded on the importance of the integrated approach to survivability from **Pywell** *et al.* (1999), notably also discussing the:

- difficulties of performing survivability balance of investment trade-offs when militarily and commercially sensitive data is needed to feed underpinning models. Such data includes the platform- and threat-related data, *e.g.* that from the US Survivability/Vulnerability Information Analysis Center (United States. Department of Defense, 2010), that is used in such trade studies, as exemplified in section 6.3 of Ball (2003).

- implications of Network Enabled Warfare (NEC). As indicated in Figure 2-1, the use of NEC via RF-enabled data linking, can greatly augment a platform's SA and, as a result, can directly lead to increased survivability.

2.2.2 EW and DAS – functionality and contribution

This sub-section describes EW and DAS functionality, and discusses their contribution to survivability against war-time threats, which are discussed in the next sub-section. Most of **the Works** and many of their references demonstrate the importance of effective EW and DAS to protecting platforms and aircrew, and maximising the probability of mission success and survival when going in harm's way. Without them platforms are essentially defenceless against the myriad of threat weapon systems in the inventories of the world's nations.

Figure 2-3, developed from **Pywell** (2004; 2010) provides a block diagram of a comprehensive generic DAS and contextualises how DAS nowadays fits into the wider picture of EW and NEC.

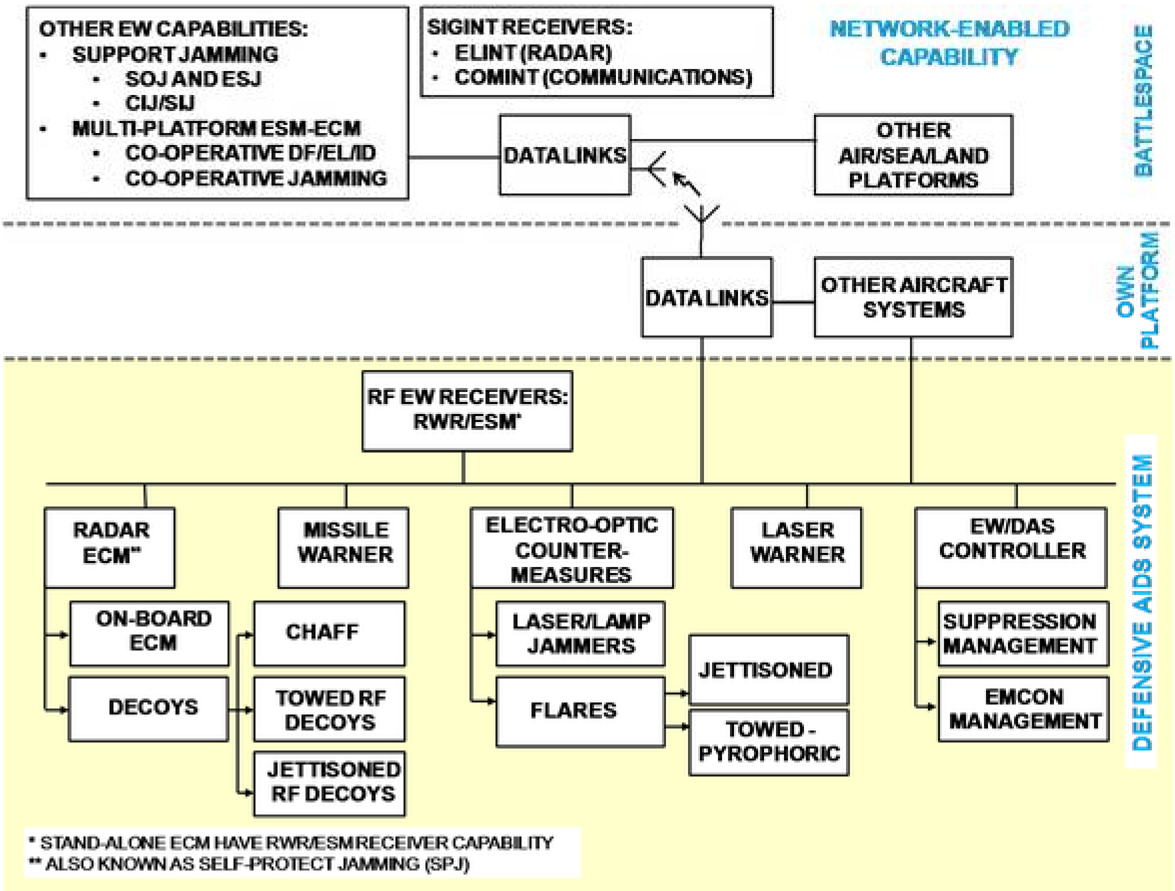

Figure 2-3: Generic DAS and context within EW

Of particular relevance to this thesis are the RF EW receivers in Figures 2-3: RWR and ESM. The importance of these receivers to survivability and the use of RF threat simulators to confirm their fitness for purpose and readiness for combat are discussed in the remainder of this thesis.

Figure 2-3 illustrates DAS complexity, with many, multi-spectral components under control of an EW or DAS controller, which, in some cases, is an integral part of the platform's main computing and control element. EW, Signals Intelligence (SIGINT) and NEC play an important part in modern air warfare and NEC scope is increasingly important to mission success and air platform survival (Wexler, 2005; Keppler, 2008).

The general functions of DAS and other EW elements in Figure 2-3 are nowadays well described in the literature, *e.g.* Schleher (1999), Adamy (2001; 2004), **Pywell** (2010) and its references, Jane's (2011a), and Welch and **Pywell** (2012) and its references. Welch and **Pywell** (2012) in particular contains informative descriptions and illustrations of typical EW systems. Specific DAS functions of all but RF EW receivers are out of scope and discussion of detailed performance characteristics is not possible in this unclassified thesis. EW RF receivers, for whose T&E RF threat simulators are used, are discussed in greater detail in section 2.3

Over the last three decades there has been an increase in DAS function (what it can do) and performance (how well it can do it). More recently, there has been a move from stand-alone DAS components to federated (linked stand-alone), then to integrated DAS, where there is no discernible boundary between DAS elements **Pywell** and Midgley-Davies (2010), Welch and **Pywell** (2012), Roberts (2013). Levels of integration continue to increase, for example some of the latest DAS have multi-spectral integration, *e.g.* RF and IR sensor and system integration (Andrews, 2008; **Pywell** and Midgley-Davies, 2010). This increased level of integration, especially of ESM-ECM, further complicates EW T&E and necessitates integrated test equipment, *e.g.* RF threat simulators working in concert with ECM RMS.

The ability to be more survivable, from an EW standpoint, is governed by the exact scope of the DAS fitted to the platform (*cf*. Figures 2-2 and 2-3), the level of NEC available and utilised, and the capability and deployment of supporting assets, in particular SJ (**Pywell**, 2010; **Pywell** and Midgley-Davies, 2010). Keppler (2008), reporting NATO RTO Study SAS-064's outcome, *cf*. Table 1-1, under-pinned the importance of NEC by concluding that, for a number of modern threat scenarios – particularly asymmetric ones, EW alone could not guarantee protection of air assets.

Keppler also concluded that successful EW deployment required close integration with other sensor and intelligence information, in line with NATO's Trial Hammer 2005, which leveraged the efforts of NIAG SG-79, *cf*. Table 1-1 (Wexler, 2005).

Figure 2-4, from **Pywell** and Midgley-Davies (2010) was developed from **Pywell** *et al.* (1999) and Pywell (2006) and shows EW's contribution to survivability.

	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/EO/IR COUNTERMEASURES • CUE SUPPORT JAMMING – STAND-OFF – ESCORT – CLOSE-IN (e.g. UAV)	• CUE OWN WEAPONS AND RF/EO/IR 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/EO/IR JAMMING & DE ATTACK: • DENY OPPONENT'S TARGETING & FIRING SOLUTIONS • DECOY INCOMING MISSILE OR FIRE	• STAND-OFF/-IN, SELF PROJECT & ESCORT RF JAMMERS • CHAFF/FLARES • EO/IR 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 2-4: Contribution of EW to survivability

Figure 2-4 indicates that, other than for BDT, where it makes no contribution, EW systems make significant and multi-faceted contributions to optimised SA and maximised survivability, to thereby increase mission success probability.

To arrive at the optimum DAS capability for a given platform, role and mission there are complex, multi-variate trade-offs to be conducted, with the trade space including threat scenario, DAS equipment technical performance, size, weight, reliability and through life affordability. This aspect is discussed throughout **the Works**, in particular in **Pywell** (2010) and **Pywell** and Midgley-Davies (2010), and the views expressed therein are consistent with those of others, *e.g.* Heikell (2005) and Law (2011).

2.2.3 Threat systems and their kill probability

Specific performance attributes of threat systems and of EW and DAS capabilities used to counter those systems are highly classified nationally. This section is thus necessarily constrained to information that has been 'public released' and that which is already in the public domain.

Threats to airborne military platforms fall into two main categories (**Pywell**, 2003; 2004; **Pywell** and MacDiarmid, 2010):

- Man-made:
  - RF-guided, IR/UV/Electro-optically-guided: AAA, AAG, AAM, DEW and SAM.
  - Weapons designed to be guided only by human eyes, *e.g.* small arms.
  - Air RF environment, comprising signals from civilian and military emitters.
- Natural: Lightning strike and cosmic radiation.

Threat types are described and depicted in **Pywell** (2004), Keppler (2008), Kopp (2009), Wallace (2009; 2010), Jane's (2011b; 2012), Air Power Australia (2013) and Zord (2013). Threat scenario intensity varies by conflict, aircraft role and mission. An unclassified indication of this is provided by Grant (2009a), showing a daily SAM firing rate of 11 (peak 43) for the 1999 Kosovo conflict and 115 (peak 190) for the 2003 Iraq war.

Each military threat weapon type has a Probability of Hit (P_H) and Probability of Kill (P_K), which can be used to quantify the effectiveness of a given threat weapon system when used in a given operational scenario against air platforms, whether stationary or manoeuvring. P_H and P_K are each a statistical function of many things: P_H is largely a function of the threat system and includes reliability of the threat's targeting system, reliability of its weapon, and probability of detecting the aircraft, whereas P_K is largely a function of the intrinsic vulnerability of the air platform (Ball, 2003; **Pywell**, 2004). Chapter 3 of Ball (2003) provides a rigorous explanation of these and associated terms, using US survivability and vulnerability terminology, which sub-divides 'kill' levels thus: aircraft immediate disintegration; fall out of control within 30s, 5 minutes and 30 minutes of being hit; and fall out of control before mission completion.

As discussed in **Pywell** (2004), each and every threat engagement is a highly probabilistic event with an uncertain outcome and many factors preventing the attacking side's goal of P_H=P_K=1. This is reflected in the non-unity overall kill rates vs. firings actually achieved in combat (**Pywell**, 2003; 2004; Kopp, 2010).

A platform's DAS and related EW capabilities, whether on-board or via NEC or SJ, can mitigate, minimise or negate the capabilities of a given threat type, *i.e.* they have a P_K Reduction Factor (P_KRF).

Of the aforementioned threats, only RF-guided weapons and the air RF environment are of relevance to RF EW receiver systems and hence to the RF threat simulator topic covered by this thesis (**Pywell**, 2007). Those EW receiver systems and their contribution are discussed in the next section.

2.3 THE IMPORTANCE OF RF EW RECEIVER SYSTEMS

RF EW receiver systems have, since the earliest days of EW, been recognised as fundamental to platform and aircrew survival when operating in hostile airspace (Northrop Grumman, 2005). They are also key contributors to the data fusion process that results in improved SA and thence enhanced survivability and improved mission success probability (Noonan and **Pywell**, 1997).

2.3.1 RF EW receiver classes and technologies

RF threat simulators are used for testing all three classes of RF EW receiver: RWR, ESM and ELINT. The boundaries between these classes, especially between RWR and ESM, have become blurred with increasing computing power and hardware component technology advances over the last two decades (**Pywell**, 2010; Holt, 2011a; Welch and **Pywell,** 2012). For the remainder of this thesis the term 'ESM' is thus taken to include 'RWR', with 'RWR' only used where specifically relevant.

ELINT cannot be discussed further in this unclassified thesis beyond referencing Wiley (1993; 2006), which covers the analysis of radar signals as pertinent to programming ESM (*cf.* section 2.3.3), and Holt (2011b), which provides open press results of a survey of ELINT receiver technology.

Figure 2-5 shows the components of a generic RF EW receiver and its interfaces to other aircraft systems.

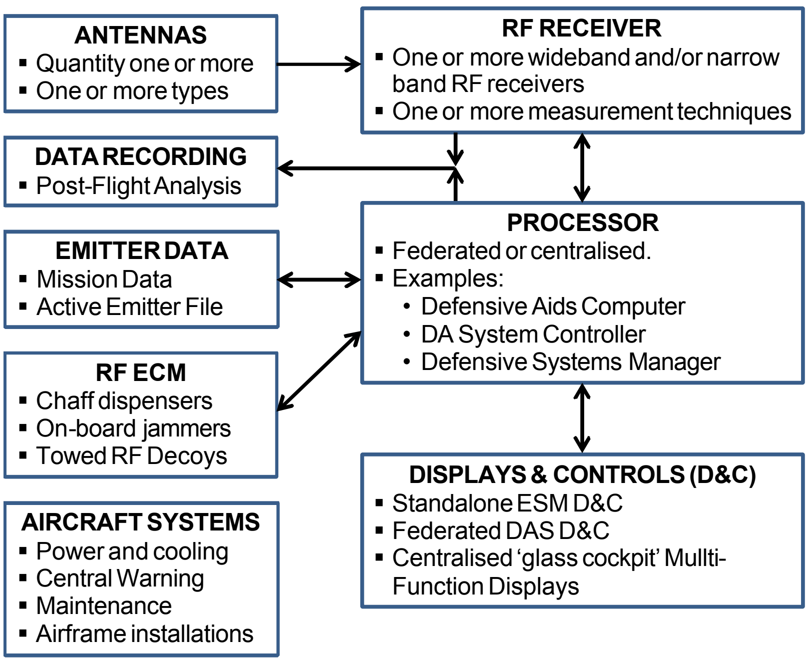

Figure 2-5: RF EW receiver block diagram

In particular the development of so-called 'digital' receiver technology has also benefitted from speed and performance advances in analogue-to-digital converters (Manz, 2012). These receivers, whose development continues at this time, have been investigated by a number of EW equipment manufacturer, aircraft companies including this author's (Pywell and Lee, 2000; Pywell, 2001; Kinsey and Pywell, 2003), and government agencies, including NIAG Study Groups 66 and 79 (see Table 1-1). They offer a number of potential benefits, including higher resolution of measured parameters, better measurement repeatability via reduced drift and less required calibrations, parallel detection and tracking of emitters within a given bandwidth, and in-flight re-programming to cater for specific and newly encountered threat emitters.

Table 2-2, updated from **Pywell** (2007) and Welch and **Pywell** (2012), shows each receiver class's characteristics and discriminating factors.

	RWR*	ESM*	ELINT
PURPOSE RECEIVER COMPONENT	**WARN AIRCREW** OF RF-GUIDED THREATS & CUE COUNTERMEASURES	**DETECT, ID & 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 CAVITY-BACKED OR CONFORMAL SPIRALS PER FREQUENCY BAND FOR AZIMUTH AND ELEVATION	INCREASED NUMBER & 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 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

Table 2-2: RF EW receiver characteristics

There are a number of receiver technologies: crystal video (wideband and tuned), Instantaneous Frequency Measurement (IFM), swept superheterodyne (wideband or YIG-tuned narrowband), wideband channelised, compressive, acoustic-optic Bragg cell, and 'digital' (Wiley, 1993; Schleher, 1999; Tsui, 2001). RF EW receivers' performance, especially as a function of increasing multi-emitter scenario density, can vary substantially dependent upon which receiver type or types are employed and the number and types of antennas used in conjunction with the receiver(s).

Although EW receiver class impacts specification of RF threat simulators utilised for their T&E, receiver technology does not generally have a major impact on that specification beyond SUT antenna interfacing, which is covered in section 2.3.2 *et seq.* Only limited reference to receiver technology is thus made in later chapters.

Key functions of ESM are DF, which includes the technically stretching case of EL, and emitter ID, and these are discussed in the next two sub-sections.

2.3.2 DF measurement techniques

The primary purpose of DF and EL is to determine the Direction of Arrival (DOA) of RF signals emanating from ground-based, naval or airborne radars. In the EL case it is also necessary to determine an accurate emitter-to-ESM range. ESM use a number of measurement techniques to determine DF and EL. The single-platform typical accuracies of the main techniques are indicated in Table 2-3 (developed from Noonan and **Pywell**, 1997 and **Pywell**, 2007). Multi-platform employment of some of these techniques can provide better accuracy, as was investigated in NIAG Study SG-79 (see Table 1-1).

SUT Technique	Typical r.m.s. DF accuracy	Application on platforms
Amplitude Comparison	3-15º	4-port is minimum capability of EW receiver systems
Phase Interferometer (Short and Long Baseline)	0.1-3º	Often forward azimuth coverage only on aircraft
Spinner	2-5º	Not normally applicable to fast jets
Multi-beam, Electronically Scanned Arrays	1.7-2º	Originally land and naval/army platforms; finding increasing use in aircraft
Time Difference of Arrival (TDOA)	0.1-2º	Complex, especially on aircraft, and needs large platform or multiple platforms for highest accuracy
Frequency Difference of Arrival (FDOA)	~2º	FDOA, a.k.a. Differential Doppler or Pseudo-Doppler, measures the frequency (RF) difference on two or more antennas. Optimally used in conjunction with TDOA. Reasonably complex, requiring high SNR and a highly accurate frequency reference.

Table 2-3: Direction finding techniques

No single receiver technology and DF technique enables the optimum but utopian full spherical coverage around the platform, with pin-point DF accuracy and precise EL, and instantaneous and unambiguous ID of all emitter types in the highest scenario densities to be realistically encountered. Each technology and technique has one or more limitations, for example those imposed by:

- physical antenna locations on the platform,
- Signal-to-Noise (SNR) constraints within the receiver system, and
- combination of processing power and very limited time (of the order of seconds) in which to ID and notify hazardous threats to aircrew and the rest of the platform's avionics and DAS, for threat countermeasure engagement.

Arguably the dominant constraint is the quantity, type and placement of ESM antennas around the airframe. Antenna placement is particularly important, to ensure appropriate angular coverage at the ESM system level, and to minimise obscuration and electromagnetic scattering caused by the airframe itself (**Pywell,** 2010; **Pywell** and Midgley-Davies, 2010).

Wyman, Murphy and **Pywell** (1999) investigated the potential for enhanced survivability through improved EL techniques by modelling Amplitude Comparison, Phase Comparison and TDOA on a small, fighter-sized aircraft. They considered potential sensor and data fusion improvements, with potential application to the general small-to-medium sized platform. It was discovered that, for a single platform, although Amplitude Comparison was useful, obscuration (shadowing) effects were problematic. Short measurement baselines and this obscuration were found likely to prevent an EL solution based on Phase Comparison or TDOA alone. Potential short term alleviators identified were 'digital' receiver, multi-platform co-operation and data-linking, or a podded EL system.

For the longer term solutions Wyman, Murphy and **Pywell** (1999) assumed technological developments in 'digital' receivers, digitised processing and data fusion would provide enhanced DF and EL, with the suggestion that multi-platform EL would likely be the more realistic solution for fighter-sized platforms. This view was borne out by the subsequent NIAG SG-79 Study (North Atlantic Treaty Organization, 2006).

Separately, following on from Wyman, Murphy and **Pywell** (1999), Pywell, Wyman and Murphy applied for a Patent, GB0005826.3, covering a towed ESM sensor that could allow a usefully longer measurement baseline to be added to enable improved single-platform TDOA performance.

Noonan and **Pywell** (1997) described an improved process for aircraft sensor data fusion and discussed the impact of then current ESM and predicted future ESM enhancements. Pywell described the contribution and limitations of ESM, with commentary on DOA determination, hostile emitter and platform recognition from measured RF signals, and emitter location using azimuth and elevation DF angles alone, by triangulation ('Lines of Bearing', LOB) and by TDOA.

Those authors then addressed potential ID process improvements, with Pywell providing a view of potential improvements in ESM capability likely to enable a step change in ESM's quality of contribution to the data fusion process. He identified key development areas at that time relevant to DF as:

- Advanced combinational EL techniques, including classical DOA and EL techniques, LOB, TDOA and FDOA. Baumann (1996), Ulman and Geranioitis (2001), Winterling (2003) and Lim, Chae and Park (2005) provide developmental examples of such combinational techniques.
- Digital receivers, whose development was in its infancy at that time.

Some modern ESM now use a number of the above techniques individually, sequentially, spatially, in concert or simultaneously to optimise the EL and threat DF and ID so determined. Multi-platform co-operative (networked) ESM is now also being developed (Thaens, 2007).

2.3.3 Threat ID, mission data and its validation

For ESM to function correctly it has to be programmed with not only the manufacturer's proprietary algorithmic software and data, but also with Mission Data (MD), which is also known as Mission-Dependent Data (MDD). MD comprises theatre-specific data and threat-specific RF and other data, and is usually loaded pre-flight. In essence the MD helps the ESM to robustly and quickly ID an emitter by enabling it to compare measured RF parameters with a library of emitter data. That library is populated with emitter data previously measured and analysed by national intelligence agencies. Example databases are the widely used NATO Emitter Database (NEDB) (North Atlantic Treaty Organization, 2012) and UK's Defence EW Database (DEWDB) (Frew, 2003; Howe, 2009). The population and threat-specific content of these libraries, which are also used to programme RF threat simulators for the T&E of EW receivers, is beyond the scope and classification of this thesis.

MD is, however, key to the:

- Resolution of emitter ambiguities within allowed timescales (of the order of a few seconds).
- Correct ID of emitters, whether hostile, friendly or neutral military, or civilian.
- Optimisation of tactics and countermeasures.

Failure to have ESM programmed with up to date MD on in-theatre threats can lead to non-recognition or mis-identification of threat emitters, and false alarms. In turn these can significantly increase the risk of mission abort and aircraft and aircrew loss. Timeliness, in particular, is crucial to survival as missile flight times can be as little as 3-4 seconds (Gosling, 2000), giving the DAS and aircrew precious little time to deploy countermeasures, *e.g.* (Great Britain. Ministry of Defence, 2013).

Pywell, in Noonan and **Pywell** (1997), identified Specific Emitter ID (SEI or SEID), a.k.a. 'fingerprinting', via fine grain measurements of various RF parameters, as a key ESM development area that would contribute to enhanced SA and survivability via ESM technology development and MD improvements. Developments since then have confirmed this view (Talbot, Duley and Wyatt, 2003; Northrop Grumman, 2005; Howe, 2009, p.60).

Figure 2-6, developed from Pywell (2006), shows the subtle interactivity between DAS function and performance, MD and tactics and training.

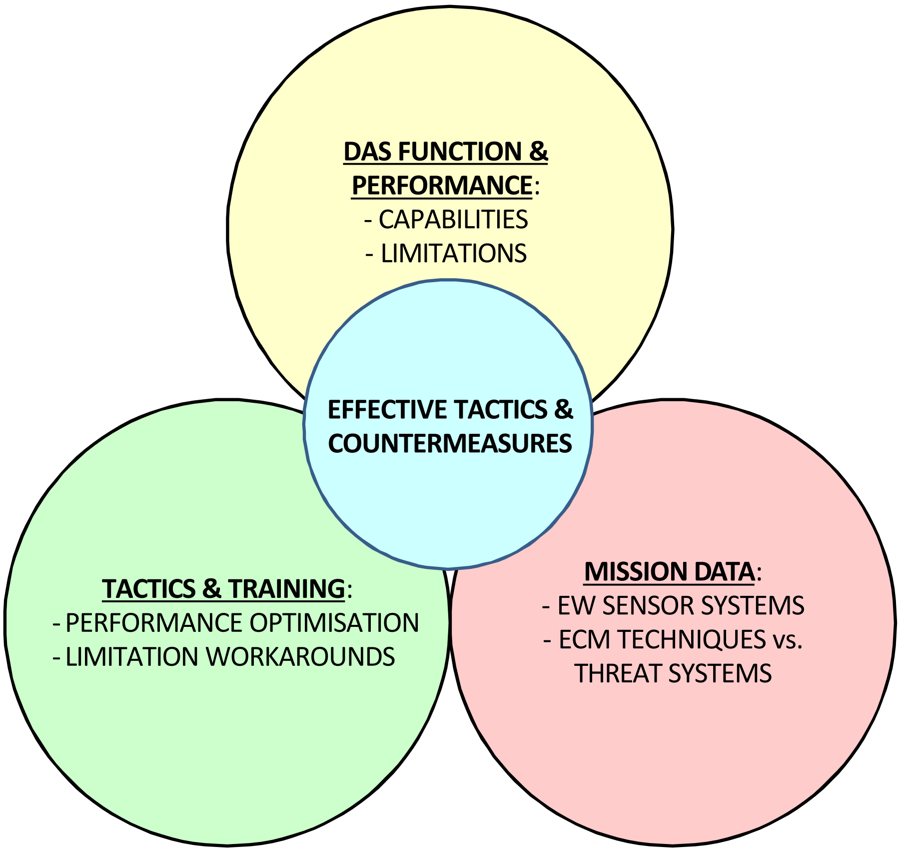

Figure 2-6: Effective tactics and countermeasures

An iterative process is usually required to assure the most effective tactics and countermeasures combination against threat weapon systems, and high-quality MD is invariably a key factor in this optimisation. This process involves MD validation, usually by a mix of ground-based T&E and flight trials. This validation of MD, when loaded into ESM, is effected by most Air Forces, sometimes with Industry support (Howe 2009; Grant, 2009b) and is:

- An essential pre-requisite of DAS clearance for operational and combat use.
- A major EW T&E mission and is conducted using high performance RF threat simulators of the types discussed in Chapters 3-5.

2.3.4 Situation awareness, ESM and combat survival

For per-platform DAS in particular, ESM are crucial to the timely detection and identification of potential and actual threats, and to the time-critical deployment of countermeasures such as on-board RF ECM, flares, chaff and off-board RF and IR decoys (towed and jettisoned).

The minimum DAS for a military aircraft that is due to go in harm's way was originally RWR for threat detection, DF and ID, and then with chaff for countermeasures. Whilst nowadays a sensible minimum DAS also needs to include a Missile Warning System and flares to address the ubiquitous IR-guided, shoulder-launched SAM threat when flying at low levels, ESM and RF countermeasures remain essential to protect against similarly ubiquitous RF-guided AAA, AAM and SAM threats. If a platform's ESM is unreliable or fails during flight this becomes a mission-critical situation. In fact, some nations' air forces will not enter combat zones if their DAS equipment (sensors and effectors) are not fully operable. Stark examples of this importance are:

- The 4 May 1982 loss over Goose Green early in the Falklands campaign of Sea Harrier XZ450 and its pilot, Lieutenant Nicholas Taylor, 800 Squadron, HMS Hermes. The pilot of the lead aircraft heard the RWR-initiated audio alarm which warned that the Argentine Oerlikon twin 35mm anti-aircraft cannons' Skyguard radar had locked onto his aircraft. This pilot released chaff whilst manoeuvring sharply, an appropriate tactic and countermeasure, thus avoiding the fire. Unfortunately for Lt. Taylor, his aircraft was not fitted with RWR so got no such warning and therefore did not evade the next deadly stream of shells. The reason it was not fitted was that, at conflict commencement, it had been the development aircraft for the Sea Eagle missile and, to cater for instrumentation installation, had had its RWR removed. It had not yet been re-fitted on that fateful day (Morgan, 2007).
- In 1995 an USAF F-16 was shot down over Bosnia by a SA-6, an elderly but still effective radar-guided SAM system (Kernan, 2000), although the pilot successfully ejected and was thereafter rescued. Subsequent successful simulation of the event by the US Air Force EW Evaluation Simulator (AFEWES) led *inter alia* to RWR re-programming improvements.

Chapter 3

PERFORMANCE EVALUATION OF RF EW SYSTEMS

3 PERFORMANCE EVALUATION OF RF EW SYSTEMS

3.1 INTRODUCTION

This chapter discusses the performance evaluation of RF EW systems in general and EW RF receiver systems in particular. The traditional approach to T&E of these systems is described and performance verification methods and locations are outlined. Three decades of EW T&E process developments are described and the key evaluation parameters for EW receiver systems, which are a major factor in driving RF threat simulator specification requirements, are identified.

Emphasis is placed on those DAS equipment that RF threat simulators are used for performance evaluation of, *i.e.*:

- RF EW Receivers, in particular RWR and ESM as used in DAS, as described in section 2.3
- RF ECM, comprising on-board RF ECM systems (jammers) and towed and jettisoned RF decoys.

In addition to the RF EW receiver focus discussed in this chapter, this author has majorly contributed to publicly available knowledge in the Research and Development (R&D), Design and Development (D&D) and T&E domains applicable generically to EW and DAS equipment, as evidenced in **the Works**, in particular Welch and **Pywell** (2012); **Pywell** and Midgley-Davies (2010) and **Pywell** (2007; 2010). Selected aspects of these **Works** and others are contextualised prior to the chapters 4 and 5 detailed discussion of RF threat simulation.

3.2 TRADITIONAL APPROACH TO EW T&E

3.2.1 Test methodology

T&E methodology has evolved substantially over the last 30 years, although the rate of evolution and the mix of methods used have varied across nations and between industries and military agencies within those nations. This section describes T&E methodology and section 3.2.2 identifies EW T&E process developments during the above period, as relevant to the testing of RF EW receiver systems. It is useful at this point to describe what T&E comprises. Although there is no single standard definition, Australian Flight Test Services (1996), see Appendix B, provides a good definition of the functions and roles of T&E in the product life cycle process, and a T&E model descriptor diagram

Pywell (2010) describes the UK defence product acceptance process, which is broadly similar to that of other major nations (United States. Department of Defense, 2005; Australia. Department of Defence, 2007). To achieve defence ministry customer acceptance from a contractual standpoint it is necessary to adequately demonstrate compliance to all specified requirements (Bail, 2008; **Pywell**, 2010), comprising those stated at the equipment, sub-system, system and air platform level. If the contract includes an off-board element, for example a communications ground station or a NEC element, then an additional level of compliance is usually required – that of system-of-systems.

As discussed in **Pywell** (2010) and Welch and **Pywell** (2012), proving compliance to specified function and performance requirements and assuring the product is fit for purpose is achieved via a qualification and Verification and Validation (V&V) methodology[8]. Qualification testing verifies design and manufacturing processes, and ensures design integrity over the specified operational and environmental range. Verification T&E is conducted by industry and seeks to confirm specification compliance, whereas Validation T&E is usually conducted by the military's operational evaluation units and seeks to confirm the product is fit for purpose, *i.e.* satisfies the military end user's needs, prior to operational service. RF threat simulators are used by industry and the military for qualification and V&V T&E of EW receiver systems and jammers.

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[8] V&V and the related terms Qualification and Design and Development (D&D) are described in **Pywell** (2007, p.558; 2010, p.4638) and **Pywell** and Midgley-Davies (2010, p.533).

Function and performance verification types are Inspection, Product and/or Process Analysis, Test and Demonstration (Bail, 2008; **Pywell**, 2010; Welch and **Pywell**, 2012). Verification Tests and Demonstrations are conducted as part of Developmental T&E (DT&E), which includes the separately identified Acceptance T&E (AT&E) used by some nations, *e.g.* Australia. Validation T&E is also known as Operational T&E (OT&E) (Benson, 1992, pp.1-3). In some nations the military T&E organisations are involved in or run the DT&E efforts with industry support, and in others platform and EW equipment providers support OT&E.

The key importance of affordability against an ongoing world-wide defence sector cost challenge has led to a three-pronged approach to T&E methodology, as follows.

Firstly, to design platforms and their systems that are 'right first time', thus requiring the minimum of testing. Although experience shows this is rarely achieved for complex systems, this situation is nowadays much better than in preceding decades as a result of:

- improved D&D processes, *e.g.* the UK's Integrated Test, Evaluation and Acceptance (ITEA) process (Great Britain. Ministry of Defence, 2009) and MathWorks (2011), and
- identification and take-up of learning points from prior projects, *e.g.* Berkowitz (1998), Stadler (2007) and Welch and **Pywell** (2012, Ch.9).

Secondly, to select the most appropriate verification method(s) to provide high-integrity, lowest-cost compliance evidence to the customer for each specification requirement. Whilst traditionally the verification method(s) for a given product were determined though experience, there are now a number of sources of guidance in the population of Verification Cross Reference Matrices, which map specification requirements *vs.* verification method(s). A good example is Bail (2008), which identifies and discusses the choice of appropriate verification method(s) *vs.* types of specification requirement.

Thirdly, to use the optimal mix of T&E capabilities to verify specification compliance, validate operational fitness for purpose, and minimise D&D cost, time and risk by earliest possible discovery and fix of any software and hardware problems (Slater and Pywell, 2012), especially those of 'Priority/Category 1' operational severity[9].

These T&E capabilities are classified into: M&S; Measurement Facilities (MF); System Integration Laboratories (SIL) – which include the UK nomenclature 'Sub-System' (SS), 'Avionic Integration' (AI) and 'Systems Integration' (SI); Hardware-In-The-Loop facilities (HITL); Installed System Test Facilities (ISTF); and Open Air Ranges (OAR). They are detailed in **Pywell** and Midgley-Davies (2010), and Welch and **Pywell** (2012, Ch.6), with further information on the use of RF threat simulators as part of those capabilities in **Pywell** (1997; 2007).

The optimal, or rather 'most affordable' T&E programme is usually jointly developed by the defence ministry contracting agencies, the platform systems integrator and systems and equipment suppliers. It is invariably not the ideal – the fully comprehensive programme that has best quality at least cost and duration with zero risk. This ideal is unattainable for a number of reasons:

- National affordability constraints and programme risk tolerance.
- Work-share arrangements on international and joint venture programmes.
- Existence and capabilities of national T&E facilities and assets, of particular relevance to adequate T&E of RF EW receivers where testing against real RF-guided threat systems, although of high quality (nothing currently matches flying against real threat systems), is both limited and particularly expensive (Olver *et al.*, 1992; **Pywell**, 2007; Welch and **Pywell**, 2012).
- Trade space between benefits and drawbacks of each type of T&E capability: performance, ease of use, location, cost and risk (Olver *et al.*, 1992; Great Britain. Ministry of Defence, 2009; Welch and **Pywell**, 2012).
- National security constraints necessitating on-shore, sovereign T&E facilities (**Pywell** and Midgley-Davies, 2010).

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[9] There are multiple definitions of problem severity categories, a.k.a. system defect priorities, *e.g.* United States. Department of Defense (1998), cited in Australia. Department of Defence (2004, p.12).

3.2.2 EW T&E process developments

From the earliest days of EW T&E, which commenced as far as EW RF receivers were concerned in the 1966 introduction of AN/APR-26 RWR during the 1959-75 Vietnam War (Jensik, 1994; Kopp, 2005; Northrop Grumman, 2005), there have been practical considerations and technological limitations of ground-based capabilities that have constrained the EW T&E process. These constraints have obliged air platform providers, systems integrators, the EW equipment industry, the military, and defence research and procurement agencies to engage in extensive flight testing and trials in order to gather appropriate qualification and V&V evidence to enable full acceptance into operational use.

- Practical considerations meant some aspects could not be ground-tested at all, *e.g.* chaff dispensing and dispersal ('blooming'), or could not be *adequately* ground-tested, *e.g.* flare performance (Slater and Pywell, 2012).
- Technological limitations, especially in the area of RF threat scenario generation for T&E of EW RF receivers and jammers (**Pywell**, 2007; **Pywell** and Midgley-Davies, 2010), see Chapter 4, led to a lengthy, costly and risk-laden iterative fly-fix-fly T&E process. EW receivers were flown against real threats on OARs and when, as was often the case, a receiver did not perform as required and specified, software/hardware fixes were developed and implemented, and the flight test or trial re-run for as many fly-fix-fly iterations as necessary to gather the required qualification and V&V evidence.

There has been, from affordability and availability for operational use standpoints, a relentless thrust internationally since those earliest times to transfer as much qualification and V&V evidence gathering from flight test toward ground-based T&E facilities and thence toward M&S. This is unsurprising given ground testing is cost-effective, although the exact benefit scope is difficult to quantify given the wide variety of systems to be tested, large numbers of test objectives and parameters, and wide range of EW T&E capabilities (OAR and ground-based).

Such transfer can offer significant programme benefits: reduced timescales, risk and cost via earlier detection and resolution of problems (Olver *et al.*, 1992; **Pywell**, 1997; Carreras, 2002; Australia, Department of Defence, 2004, p.9; Stecklein, 2004; Slater and Pywell, 2012). Olver *et al.* (1992) reported two sets of numbers that indicate ground testing, where viable for a specific test, is 86-93% cheaper than flight testing for achieving the same test objectives.

Figure 3-1 shows a current international view of the EW T&E process. This is in line with an international view provided in Figure 1-6 of Welch and **Pywell** (2012, p.1-12), the NATO EW T&E handbook. The latter figure was developed from that in Banks and McQuillan, eds. (2000). The application of this generic T&E process and its subservient processes and procedures has varied from nation to nation and with time since the beginning of EW RF receivers' testing in the early 1960's.

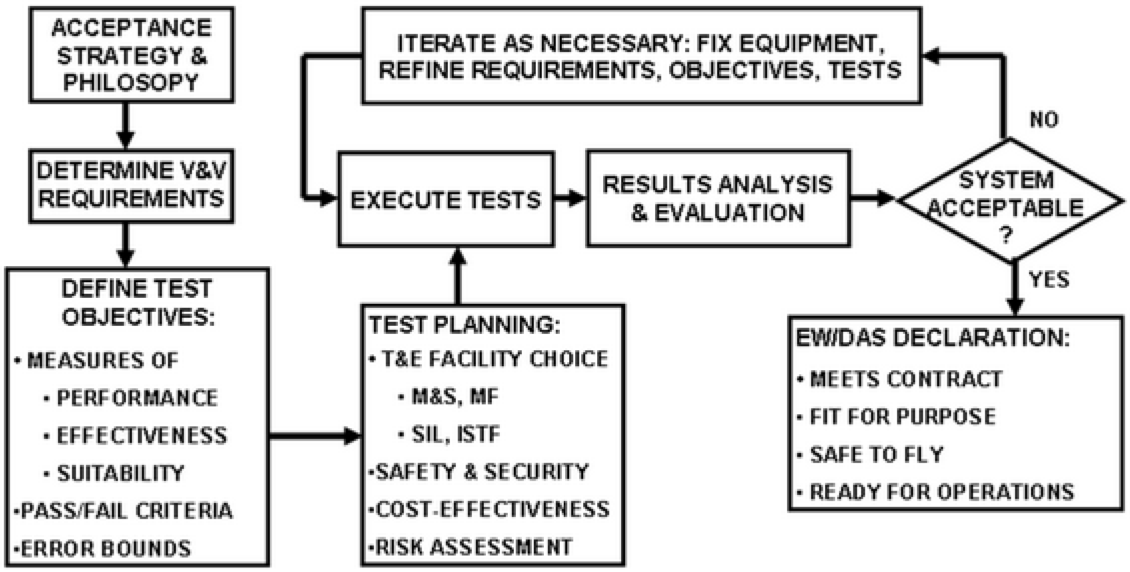

Figure 3-1: EW test and evaluation process (with permission, Wiley and Sons Ltd.)

Most nations producing and using early EW equipment commenced by developing disparate, type-specific (per-EW equipment, per-DAS, per-platform) qualification and V&V test procedures and T&E methodologies in the absence of an over-arching T&E process or a dedicated EW T&E process. Most have by now progressed to the situation where EW equipment suppliers, platform and systems integrators, and defence agencies and the military have test processes and procedures that comply with national over-arching T&E processes with, in some cases, dedicated and/or mandated EW T&E processes.

Table 3-1 indicates a non-exhaustive, open press chronology of known T&E process developments as pertinent to EW T&E. Some are specifically EW and others over-arching policies, processes or guidance, but all have contributed to the current robust process.

Process/Policy/Guidance	Reference and notes
DOD Test and Evaluation Process for Electronic Warfare Systems - A Description	United States. Department of Defense (1994)
AF-MAN-112: EW T&E Process – Direction and Methodology for EW testing	United States. Department of Defense (1995). Implements AFI 99-103 for EW
Electronic Warfare and Radar systems Engineering Handbook	United States. Department of Defense (1999). NAWCWPNS TP 8347, Rev 2 of 1 April 1999
NATO RTO AG-300-V17: EW Test and Evaluation	Banks and McQuillan (eds.) (2000)
DI(AF)LOG 2-7: T&E of Technical Equipment	Australia. Department of Defence (2001)
T&E Management Guide	United States. Department of Defense (2005)
Defence T&E policy	Australia. Department of Defence (2007)
Defence T&E Strategy	Great Britain. Ministry of Defence (2008)
AFI 99-103: Capabilities-based T&E	United States. Department of Defense (2009)
ITEA	Great Britain. Ministry of Defence (2009); Walters and Perks (2011)
NATO RTO AG-300-V28: EW Test and Evaluation handbook	Welch and **Pywell** (2012) Supersedes AG-300-V17.

Table 3-1: Chronology of T&E process development relevant to EW

Of these, the most current international EW T&E process handbook is Welch and **Pywell** (2012).[10] Produced under NATO RTO SCI Panel Task SCI-203, *cf.* section 1.1.2, it is the result of a 2009-12 extensive update to the original handbook, AGARDograph 300 Volume 17, Issue 1 (Banks and McQuillan (eds.), 2000), which it superseded. The update comprises an extra 216 pages and 108 figures/tables. It is considered by Flight Test Group 3, the SCI-203 sponsoring agency, as a benchmark for future NATO AGARDographs, *cf.* Appendix A (SCI-203 Champion's commendation).

[10] *"AGARDographs (Advanced Guidance for Alliance Research and Development) constitute the principal formal category of publications for work prepared by, or on behalf of, Science and Technology Organisation panels. An AGARDograph must pertain to a single, clearly defined subject and comprise material generally agreed to be of lasting interest." (North Atlantic Treaty Organization, 2013c)*. Two series of AGARDographs exist, 160 (Flight Test Instrumentation: 22 Volumes) and 300 (Flight Test Techniques: 28 Volumes).

Table 3-2 indicates the key substantially updated elements, which gives an indication of the addition to the body of knowledge in the EW T&E domain and its widest possible transfer via 'public release' availability on the internet.

		AG-300-V17		AG-300-V28		INCREASE		This author's contribution
Section	Content	Pages	Figures/ tables	Pages	Figures/ tables	Pages	Figures/ tables	
Chapter 6	EW T&E Facilities and Resources	4	4	27	23	23	19	88%
Chapter 7	Modelling and Simulation	6	2	27	10	21	8	97%
Chapter 9	Learning from Experience	4	2	28	2	24	0	96%
Annex A	Electronic Warfare Test Facility and Resource Descriptions	23	4	42	19	19	15	50%

Table 3-2: Substantially updated sections of NATO EW T&E handbook

Of additional note is the significant expansion of the Learning from Experience chapter, which includes the co-authors' hard-won knowledge from EW T&E, including RF receiver testing and operation of RF threat simulators.

From an EW T&E process viewpoint, there has been much progress in the quest for more cost-effective EW T&E and reduced EW flight test and trials in the last three decades. This has been enabled largely by computing power advances since the 1970s and a much improved understanding of electromagnetic and systems engineering for military air platforms (**the Works**; Moir and Seabridge, 2008). Three, high impact, EW RF receiver-relevant examples of major steps in this move away from EW T&E programmes predominated by flight testing are:

- Technology advances in RF threat simulation (**Pywell**, 1997; 2007; **Pywell** and Midgley-Davies, 2010), the primary theme of this thesis.
- Modelling of flare dispensing. Slater and Pywell (2012) showed how full certification could be achieved via M&S augmented by a small number of flights compared to traditional, flight test-intensive flare clearance programmes.
- Advent of aircraft-sized anechoic chamber ISTFs with RF threat simulators, with their many benefits (Olver *et al.*, 1992; **Pywell** and Midgley-Davies, 2010; Welch and **Pywell**, 2012). Figure 3-2 shows such a UK facility, the EWTF (in which this author was a key outset and mid-life upgrade player), and Table 3-3 provides a chronology of known US and European facilities.

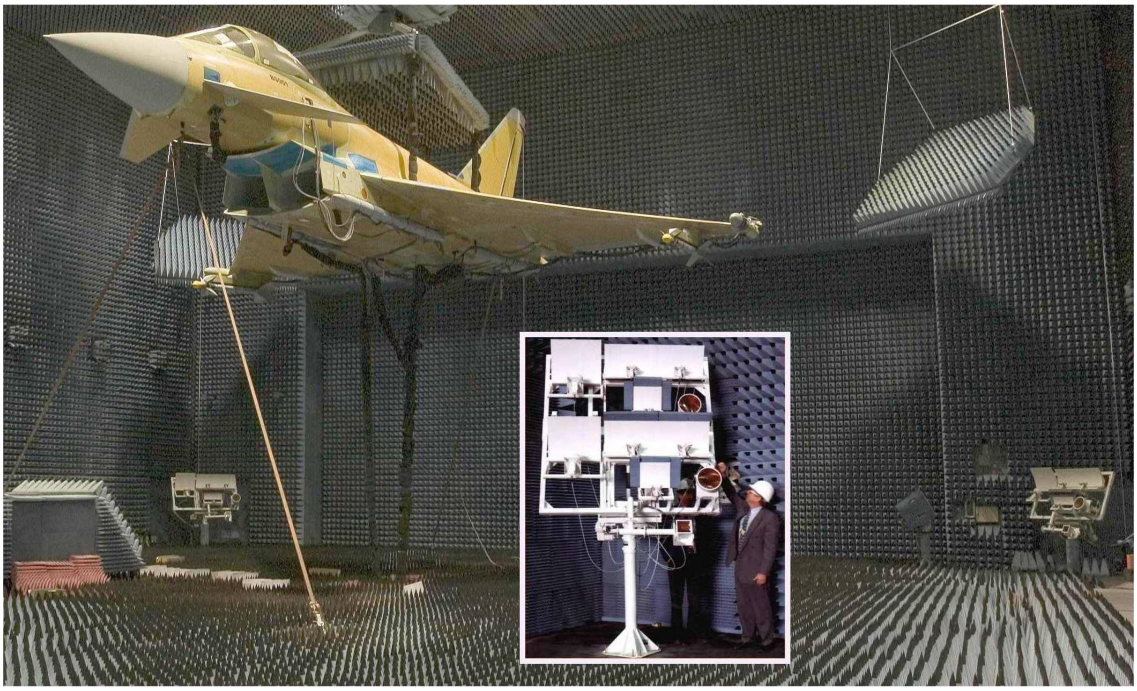

Figure 3-2: Typical ISTF: BAE SYSTEMS' EW Test Facility (UK)

ISTF name	Location	First operational
Grumman Aircraft Anechoic Test Facility (AATF)	Calverton, NY, USA	1968
US NAVAIR AATF	Patuxtent River, MD, USA	1983
Lockheed Martin Engineering Test Facility	Fort Worth, TX, USA	1987
Horton Joint Pre-flight Integration of Munitions and Electronic Systems (J-PRIMES)	Hangar 68, Eglin AFB, FL, USA	1988
AFFTC Benefield Anechoic Facility (BAF)	Edwards AFB, CA, USA	1989
EW Test Facility (EWTF)	BAE SYSTEMS, UK	1998
US NAVAIR Advanced Systems Integration Laboratory (ASIL) – Large Anechoic Chamber (LAC)	Patuxtent River, MD, USA	1999
Alenia AATF	Turin, Italy	2008

Table 3-3: Operational dates for selection of aircraft-sized anechoic ISTFs

Although some believe all qualification and V&V evidence gathering may one day be achieved through the use of M&S alone, **Pywell** and Midgley-Davies (2010) noted that this is unlikely to be wholly realised for EW, due to a combination of:

- practical constraints, *e.g.* those identified above and RF/IR jamming effectiveness evaluation, which require simultaneous human, atmospheric and (real or simulated) threat interaction with the aircraft and its EW systems, and
- residual technological limitations of ground-based EW T&E capabilities, *e.g.* sub-optimal RF threat simulation fidelity, see Chapter 5.

It is now generally understood that, whilst much EW qualification and V&V evidence can be adequately acquired via ground-based testing, some T&E aspects still and will continue to require verification via flight test. These include OT&E aspects such as tactics and countermeasures development and EW effectiveness optimisation (Wallace, 2009; 2010; **Pywell** and Midgley-Davies, 2010).

3.3 EW RECEIVER KEY EVALUATION MEASURES

To confirm that an EW receiver system is suitable for operational evaluation by the military prior to combat use it is necessary for industry to verify a number of key evaluation measures and their underpinning parameters. These are nowadays invariably verified by test and analysis, rather than by other verification methods. Most require the use of RF threat simulation equipment.

These measures and parameters are similar for all classes of RF EW receiver, *cf.* section 2.3.1, but some may differ dependent on the receiver class and capability, *e.g.* those capable of EL, and type of receiver technology. Table 3-4 provides, in no particular order, an unclassified view for an EW receiver forming part of a DAS (Noonan and **Pywell**, 1997; United States. Department of Defense, 1999; Adamy, 2001; **Pywell**, 2007; Welch and **Pywell**, 2012). Of note is that many of the measures and parameters are inter-linked within the receiver system to enable its best possible formulation the cardinal outputs of ID, direction and location of RF-guided threats.

Key Evaluation Measures and Parameters	
DF accuracy (largely dependent on own-aircraft antenna types, numbers and installations)	Detection sensitivity, including Minimum Discernible Signal (MDS)
Frequency range, modulation (for CW and pulsed RF signals) and selectivity (two or more signals in close frequency proximity)	High signal density performance, for un-degraded performance in operational RF environments
Pulse Width, amplitude, range and patterns, *e.g.* missile guidance (pattern of pulse spacing within a pulse group)	Maximum dynamic range, to cater for signals with very different amplitudes
Pulse Repetition Interval and modulations	Probabilities of Detection & Intercept
Radar scan type and rate, *e.g.* rotating, sector scanning, nodding	Missed alarms and non-detection and/or display of threats
Threat geo-location accuracy and time to locate	Signal amplitude and phase
Accuracy and timeliness of cueing and triggering of defensive and offensive countermeasures	Quantity, type and frequency of false alarms and emitter mis-reports
Correctness of threat prioritisation	Threat range/pseudo-range accuracy
Radar lobe characteristics (beam width, lobe amplitude & positions)	Time to correctly ID threat and non-threat emitters, with lack of ambiguity
Emitter, mode and associated platform ID, each with a recognition confidence factor	Time of Arrival accuracy
Receiver tuning time and signal acquisition speed	Immunity to jamming
Simultaneous signal capability	Threat signal polarisation
Maximum instantaneous analysis bandwidth	

Table 3-4: Key evaluation measures and parameters for RWR/ESM

Chapter 4

RF THREAT SIMULATION

4 RF THREAT SIMULATION

4.1 INTRODUCTION

This chapter introduces RF threat simulators, explains their prominent position in the EW T&E armoury and outlines the likewise importance of the complementary EW T&E equipment, ECM RMS. The subtle terminology differences between the terms ‘simulation’ and ‘emulation’ are briefly discussed ahead of a fuller discussion in chapter 5. Threat simulator importance to EW T&E transfer from flight to ground-based test is considered. Threat simulator origins are described, from the earliest and simplest laboratory test configurations to the latest, highly complex threat simulators, as now used world-wide for qualification and V&V testing of modern and legacy RF EW receiver systems.

The terms ‘simulator’ and ‘stimulator’, and ‘simulation’ and ‘stimulation’ are, as is the norm in the EW field, used synonymously in this thesis. The RF threat simulators that are discussed in this thesis do both:

- They use computer modelling and digital and RF hardware to produce a *simulation* of the air RF environment, and
- They are used to *stimulate*, at RF, the EW receiver under test with that *simulation*.

Whilst this thesis focuses on the simulator type used in SILs, HITL facilities and anechoic chamber ISTFs, there is also appropriate discussion of the types of threat simulators used on OARs later in this chapter and in chapter 5.

4.2 THREAT SIMULATORS AND ECM RESPONSE MEASUREMENT SYSTEMS

RF threat simulators and ECM RMS are key tools for qualification and V&V T&E of EW receiver and jammer systems. Together they have played and continue to play a significant enabling role in the transfer of much EW T&E effort from flight testing on specialist OARs toward ground-based testing in SILs, HITL facilities and anechoic chamber ISTFs, underpinned by validated models.

4.2.1 RF threat simulators

RF threat simulators, in particular, have made the most significant contribution to this major shift, since the early 1970's, from expensive, limited capability and difficult to repeat flight testing and trials on RF EW receiver systems, to cost-effective, controllable, repeatable anechoic chamber, SIL and HITL testing (**Pywell**, 1997; 2007; Ali, 2002; Anderson *et al.*, 2005; **Pywell** and Midgley-Davies, 2010; Welch and **Pywell**, 2012).

Whilst this thesis covers threat simulators which are used to stimulate EW RF receivers using either directly-coupled or radiated RF signals, there is some commonality with those simulators that are used to develop and test receiver systems *via* Intermediate Frequency (IF) or digital-level stimulation of the relevant part(s) of those systems. Whilst these other types are useful during the D&D process, RF-level threat simulators provides superior T&E and investigative capability as they support the only T&E method that includes all the RF elements of the receiver system – the areas where technology limitations can limit or adversely impact receiver performance.

Figure 4-1, developed from **Pywell** (2007), shows the structure and content of a generic RF threat simulator, indicating the aforesaid commonality. It provides:

- a top-level schematic for an ECM RMS and indicates how such T&E equipment is used in conjunction with RF threat simulators for laboratory, anechoic chamber and OAR T&E of RF EW receivers.
- an indicative breakdown, for a modern multi-emitter threat simulator, of the software, digital and RF content of a simulator's three main functional elements: control and operator interface, digital generation, and RF generation and distribution.

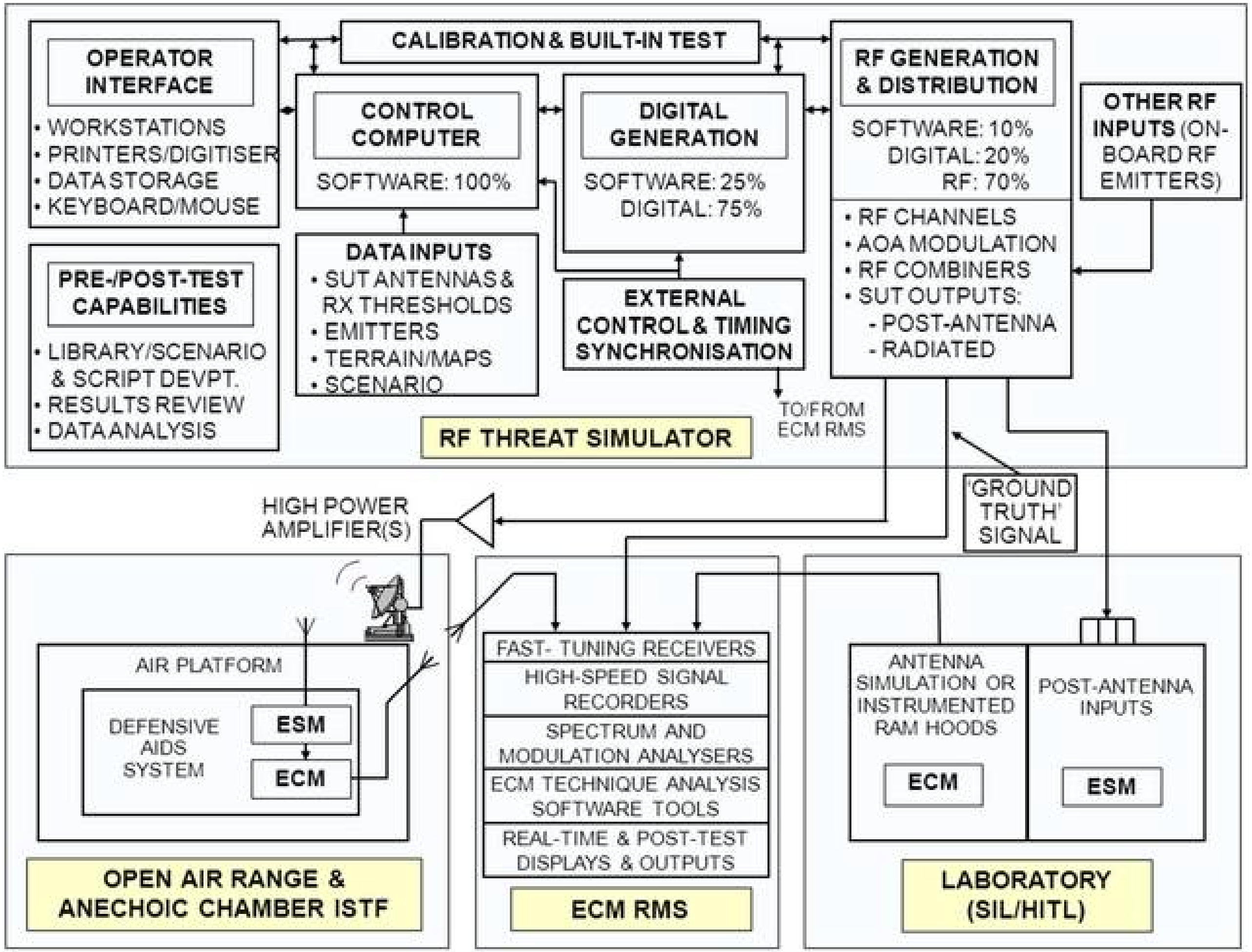

Figure 4-1: Generic RF threat simulator structure and content

The term 'threat simulator' is nowadays a general term used to describe all RF simulation equipment, whichever EW T&E facility it is used on:

- of whatever capability, from single-emitter to thousands of emitters,
- whether wide-band or with one or more narrow frequency bands,
- whether simulating threat emitters only, or – as is now the norm for laboratory and anechoic chamber use – simulating multiple threat and non-threat military emitters, and civilian emitters.

RF threat simulators are also known as 'RF Emitter Generators' (RFEGs), in recognition of the prior-mentioned subtle difference. In this thesis the terms 'threat simulator' and 'RFEG' are interchangeable.

This author led the specification of all major RFEGs purchased for testing RWR and ESM at his company's UK T&E centre over the last 22 years. In addition to being the lead RFEG technical specialist, he was Engineering Manager for the five most recent RFEGs and two RMS purchased, and Project Manager for three of those RFEGs and one of the RMS. One RFEG and RMS pair of these was a mid-life instrumentation 'refresh' for his division's anechoic chamber ISTF – the EWTF, *cf.* Figure 3-2 (**Pywell** and Midgley-Davies, 2010).

A major difference between ground-based and OAR use of threat simulators is that those on OARs are generally 'closed loop', *i.e.* the threat simulator's output changes as a result of being jammed by the SUT (as it would in combat), whereas those used in the SIL, HITL and ISTF are generally 'open loop', *i.e.* the simulator's output does not change as a result of jamming by the SUT. Some HITLs have closed-loop simulator capability and those facilities are known as being 'EC-capable'. The SIL/HITL/ISTF threat simulators discussed in this thesis are predominantly of the open-loop type.

Ahead of the Chapter 5 discussion of multi-emitter scenario fidelity requirements and technology developments, it is useful to define some key terms (**Pywell**, 2007):

- **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.
- **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.

The relatively recent move from stand-alone RWR, ESM and ECM systems, through federated or partially integrated DAS, to fully integrated DAS with ESM-ECM has made T&E of these RF EW systems more complex (**Pywell** and Midgley-Davies, 2010; Welch and **Pywell**, 2012). For modern DAS with fully integrated ESM-ECM a similarly integrated RFEG and RMS is needed to support qualification and V&V T&E – especially in the area of threat detection, identification and location, and timeliness of countermeasure engagement.

4.2.2 ECM response measurement systems

ECM RMS can take many forms:

- from relatively simple architectures – stand-alone or networked individual items of test equipment, *e.g.* spectrum and modulation analysers, operated by specialist engineers (Sabat, 2012, p.23),
- to those early ones used on OARs, *e.g.* CERES (Annex 1 of Banks and McQuillan, 2000),
- and to the latest RMS, *e.g.* SMS (**Pywell** and Midgley-Davies, 2010) and the ECR's Slate Range Facility's Signal Monitoring System (SIMON) (United States. Department of Defence, 1996; Stepp, 2007).

In each case the measurement and analysis of ECM techniques and waveforms is complex, requiring operators with considerable RF knowledge and analytical skills. ECM RMS primary capabilities are to:

- Verify RF threat simulation RF outputs are appropriate representations of emitters for the tests to be conducted, *i.e.* the 'ground truth'.
- Measure and analyse ECM techniques, waveforms and timeliness.
- Characterise the RF environment within an anechoic chamber ISTF, including measurements of non-ECM RF emanating from the SUT.

Figure 4-2 shows a typical, modern, high-end threat simulator and ECM RMS, the commercially available CEESIM and SMS products, as used for EW qualification and verification T&E in this author's company's UK Division's SILs and anechoic chamber ISTF in the North-West UK. This type of equipment is also used by other aerospace companies and many military and defence agencies world-wide for the V&V of EW receiver and jammer performance and effectiveness.

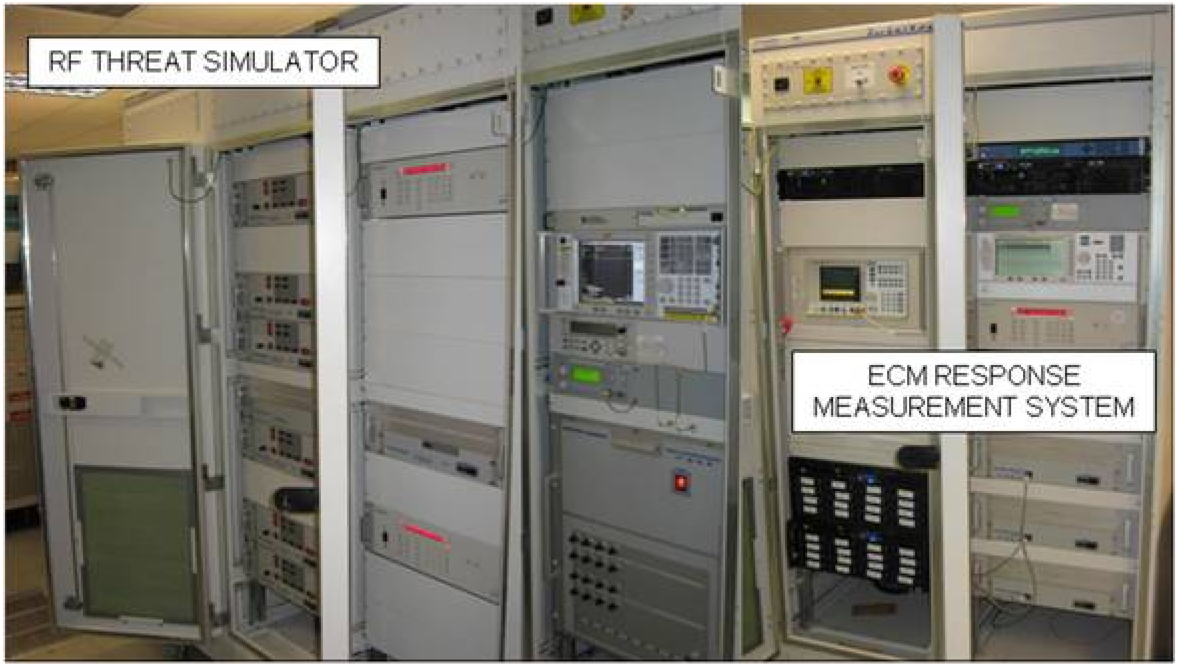

Figure 4-2: CEESIM and SMS

4.2.3 Importance to EW T&E transfer to ground test

As discussed in **Pywell** (1997; 2007), Banks and McQuillan (2000), Ali (2002), Anderson *et al.* (2005), **Pywell** and Midgley-Davies (2010), and Welch and **Pywell** (2012), the use of threat simulators in the laboratory and anechoic chamber ISTF offers significant benefits over flight testing, in particular:

- Test controllability and repeatability:
  - especially of required precision measurements – which are easily made in the chamber and laboratory but are extremely difficult to do in flight.
  - Weather independent testing.
  - Electromagnetically secure and quiet ISTFs.
- Improved problem discovery capability:
  - Earlier problem discovery prevents or mitigates surprises during flight test and trials, and in military service.
  - Easier and more comprehensive investigation of most problems is possible in ground-based T&E facilities.
  - Enhanced real-time and post-test capabilities in ISTF/SIL/HITL facilities leads to optimised use of costly OAR time and valuable range test slots.

- Reduced overall cost of T&E programme, including lower time and through-life cost of laboratory- and chamber-based RF threat simulators than actual threat systems.
- More operationally representative tests:
    - Numbers of emitters and laydowns in test scenarios
    - More realistic overall signal densities
    - Parameter ranges not available on OAR, *e.g.* frequency, PRI.
- Fewer safety constraints than OARs, and reduced risk of
    - Programme schedule over-run,
    - SUT technical under-performance on delivery to military end user, and
    - Loss of aircraft and hazards to aircrew and ground personnel/assets.

Welch and **Pywell** (2012) noted that correlation of results between different test stages, usually on different test facilities, was problematic. Test engineers must understand the underlying reasons for these differences to be able to ascertain whether a SUT problem or a T&E facility-induced artefact is the root cause. Whilst the OAR is often viewed as the most authoritative source of test data, such correlation can be difficult as the OAR is usually constrained in capability, *e.g.* quantity and fidelity of threats, when compared to ISTFs, SIL and HITL facilities.

Richard (2004) agrees with the above views, noting that an aircraft is not a good integration platform – trouble shooting expertise is in the laboratory, not in the air. Richard indicated a target problem discovery goal of 91% in the EW (sub-system) HITL, 6% in the Avionics Integration Laboratory and 3% during flight test, and noted that, to that date in that platform's (the F-22's) T&E programme:

> *"To date, there have been no (as in zero) dynamic EW problems identified during flight test." (Richard, 2004, p.23).*

Figure 4-3, shows a typical SIL/HITL facility configuration concept for EW receiver testing. The Advanced Dynamic Radio frequency Simulator (ADRS) is of the CEESIM threat simulator type.

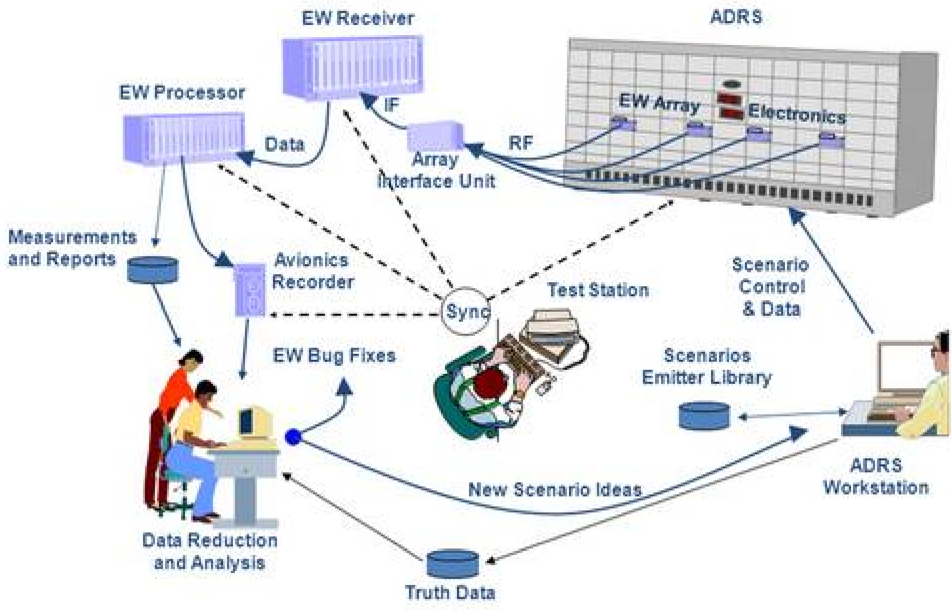

Figure 4-3: EW receiver test configuration concept
(From Richard, 2004)

Richard's target is consistent with that of Pywell and Sarti (1991), who conducted internal company research that indicated that it should be possible to find over 85% of EW systems' integration problems using ground-based EW T&E facilities (**Pywell,** 1997).

Actually achieved performance against the above targets for real EW systems is generally not releasable but anecdotal evidence suggests that these high rates are nowadays are being achieved for new and upgraded EW equipment when the best practice EW T&E chronological route is followed, *i.e.*:

- EW/DAS equipment and sub-system integration on SIL and HITL facilities,
- then EW/DAS integration with other avionics and aircraft equipment in a SIL,
- followed by installed performance testing on ISTFs (open air test sites and anechoic chambers), and
- finally followed by flight testing and trials on OARs.

4.3 ORIGINS AND EARLY DEVELOPMENT

This section describes the origins and early development of RF threat simulators, ahead of the Chapter 5 more detailed discussions of the development and management of threat simulator technology.

4.3.1 Threat simulator common attributes

Threat simulators, whether of the OAR or SIL/HITL/ISTF type, share some common top-level features and capabilities, primarily the ability to generate simple and complex emitters, of various types, with appropriate levels of emitter parameters' technical accuracy for the tests to be conducted. They are also capable of generating time-scripted single-emitter (at minimum) and multi-emitter (common nowadays) RF scenarios. They have a number of key components, cardinal functions and features (Eberl, 1998; 2009; **Pywell**, 2007), which apply to one or more T&E facility types as shown in Table 4-1.

Key component	Cardinal function	Key features
RF emitter model (OAR, ISTF, HITL, SIL)	Pulsed and CW RF generation	Signal parameter definitions, *e.g.* frequency, PW, PRI, RF power and modulation parameters
	Transmit antenna characteristics	Equipment characteristics, *e.g.* beam and scan patterns and rates
Propagation and atmospheric effects model (SIL, HITL)	Signal transmission effects between SUT antennas and each emitter	Absorption attenuation; ducting; surface types (sea state and terrain roughness); multipath (sea, land, other platforms); polarisation effects; terrain screening and blocking; emitter-SUT relative geometry; dynamics of own platform and emitters
SUT antenna and receiver model (SIL)	SUT and host aircraft effects	Antenna patterns and dispositions on airframe; DF techniques; receiver threshold models

Table 4-1: RF threat simulator components, functions and features

4.3.2 OAR threat simulators

At the outset of OAR EW T&E, in the 1960's Vietnam War era, suitable pilot training and effectiveness testing of receivers and jammers could only be carried out against real threats (if available) on OARs, as anechoic chamber ISTFs did not yet exist and laboratory threat simulation capabilities were limited.

The EW Threat Environment Simulation (EWTES), now named EC Range (ECR), on the 'Echo' range at China Lake, California, is the first known EW OAR and was established in 1968 following the 1965 SAM shoot-down of a US plane (Williamson, 2000; United States. Department of Defense, 2012a). Lack of real threat radars meant simulators had to be used, but technological limitations were very pronounced in those early days (Benson, 1992, p.14). Nevertheless, those provided were useful in the absence of anything better at the time to support D&D and T&E of RWR and ECM systems, and this resulted in improved EW protection of US aircraft during that war (Williamson, 2000).

Information on problems with threat simulation capabilities on OARs is generally not releasable but, as an indication of those earlier problems, United States. Department of Defense (1988) reported simulators mis-representing threats, with 35 out of 46 different simulators examined having substantial deviations from intelligence estimates of threat characteristics. The General Accounting Office auditors noted that deviations

> *"involved technical characteristics of the associated radars which affect the system's range, accuracy, and resistance to countermeasures, and thus the overall effectiveness of the air defense system." (United States. Department of Defense, 1998, p.3).*

and included radar power, frequency agility, radar beam size and pulse repetition frequency. It was concluded that these problems could easily distort test results on EW systems and degrade EW training effectiveness, but the auditors could not find firm evidence from V&V trials to prove this.

The ECR has developed substantially over the years and now includes a number of real threat radar systems. Stepp (2007) provides an excellent overview of OAR multi-spectral threat simulation at the ECR, along with photographs of some of those real threat radar systems. It remains a primary OAR for test and trials of US and international EW systems, including ESM and ECM (Stepp, 2007; Albert, 2011).

OARs also exist in Europe, with the UK's 1977-inaugurated EW Tactics Range at RAF Spadeadam and the US/French/German Polygone Multi-national Aircrew EW Training Facility (MAEWTF) being the foremost EW ranges (Wallace, 2009; 2010; **Pywell** and Midgley-Davies, 2010, p. 538; Welch and **Pywell**, 2012, p.6-20).

As will be explained in Chapter 5, now there is much better understanding of the simulator-surrogate-emulator-real threat trade-off, it is reasonable to believe that the above-described early-day problems have either been resolved technologically or the T&E process tailored to accommodate any less-than-perfect threat simulation aspects that are critical to each test point requirement.

Nevertheless, the fundamental limitations of OARs described in Welch and **Pywell** (2012, p.6-21) remain when compared to the comprehensive T&E activities now possible during SIL, HITL and anechoic chamber ISTF testing using multi-emitter RF threat simulators.

4.3.3 Threat simulators for laboratory and chamber use

The general evolution of RF threat simulation for SIL, HITL and ISTF use can be summarised as the development from one-emitter-at-a-time capability, providing simplicity and utility but limited realism and many constraints, to much improved fidelity single emitter simulators and, separately, to multi-emitter scenario capability, with improved realism but still with constraints.

The origins and early development of RF threat simulation for laboratory and anechoic chamber ISTF use is best described thus:

- use and integration of standard and specialist laboratory test equipment to provide single emitter simulations at RF, and
- development, since the late 1970's, of RF threat simulators with true multi-emitter scenario capability, as described in **Pywell** (2007) and as will be discussed in more detail in Chapter 5.

The earliest and simplest laboratory test configurations were generally interconnected stand-alone items of standard laboratory test equipment, at minimum a microwave RF source, typically a Voltage-Controlled Oscillator (VCO) and a PIN[11] diode driven by a pulse generator to produce a pulse-modulated RF signal for direct injection into an EW RF receiver, or for radiation, *via* a transmit antenna, at the receiver's antenna(s). In due course better RF sources became available, *e.g.* synthesised sources.

Dependent upon test requirements, these configurations were usually adequate, but, due to their great simplicity when compared to operational air RF environments, many problems tended to be found later during V&V flight test and trials (**Pywell**, 1997). Figure 4-4 shows a typical test configuration, as used by this author in the early 1980's. Such configurations were common at that time (Agilent, 2004, p.5).

[11] P-type – Intrinsic region – N-type semiconductor.

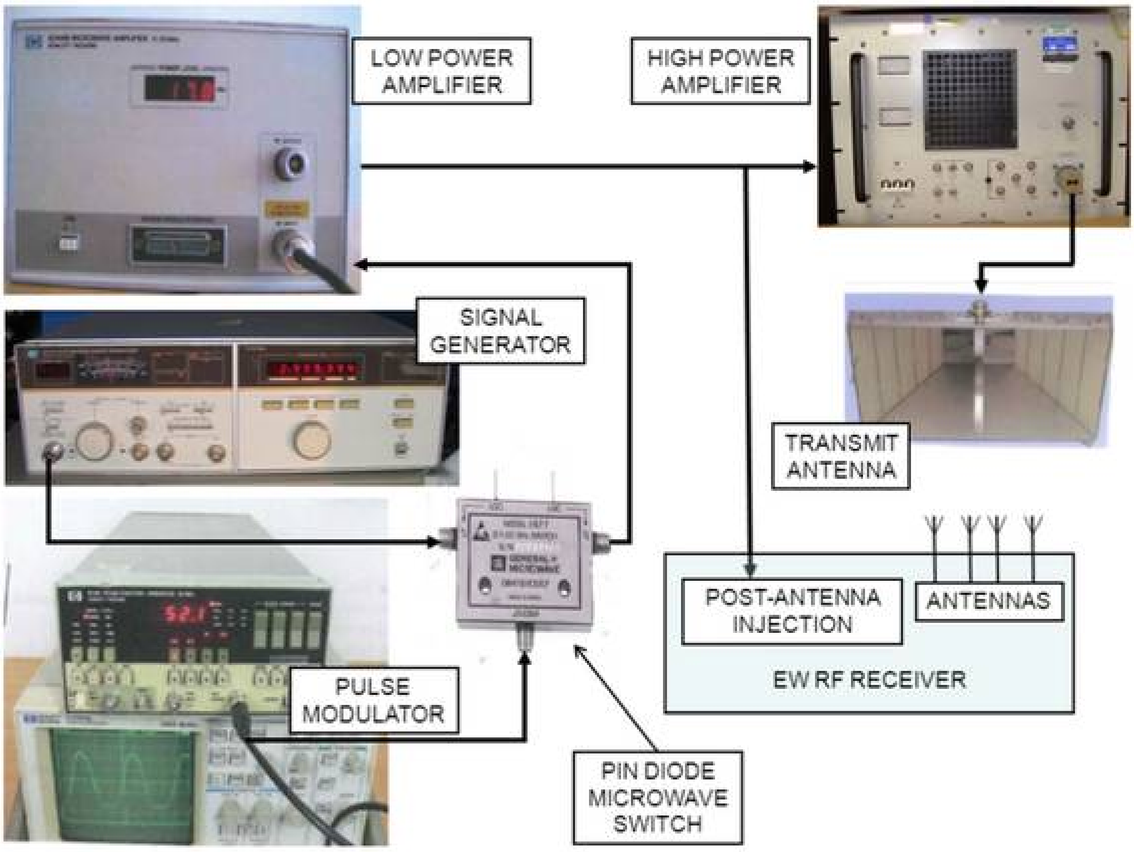

Figure 4-4: RF threat simulation - early test configuration

In addition, multiple, simultaneously transmitting emitters could only be generated by duplicating the test equipment, which quickly became cost-prohibitive for more than a few emitters. Improved control and sequencing of emitters and their characteristics was possible once computer control of test equipment *via* IEEE 488 databus became generally available. This author led a team who developed and used such a system in the mid-1980's, the EW Environment Generator (EWEG), which was controlled by a HP9845B computer and used a simple database of threat emitter parameters.

Pywell (2007) described the origins of commercially available, multi-emitter RF threat simulators. He reported that, prior to 1977, the only commercially available multi-emitter simulator was believed to be the Antekna Standard Threat Emitter System, but this was similar to the EWEG in architecture and with similar simulation limitations. The development commenced in 1997 of the first time-shared, highly multiplexed, dense environment simulator, the Tactical EW Environment Simulator (TEWES). By 1983 it had been developed into the Advanced TEWES, the forerunner of the CEESIM simulator.

Pywell (2007) also noted that EW receiver manufacturers often tended to utilise bespoke, in-house developed simulation equipment and that little open information existed on these systems. Since **Pywell** (2007) it appears that more of these manufacturers are moving away from bespoke systems, which often have high maintenance and repair costs, toward commercially available simulators. Exceptions to this are specialist governmental facilities, *e.g.* US AFEWES, who develop and maintain high-grade simulations of individual emitters. These are usually bespoke (and thus expensive to acquire and operate) – this thesis focuses on commercially available threat simulation.

Pywell (2007) stated that there had, since the 1970's, been a gradual decline in the number of threat simulator manufacturers. Table 5 of **Pywell** (2007) showed only five suppliers remained of major, multi-channel RF threat simulators. Since then one of the major simulators, the Advanced Multiple Environment Simulator (AMES), the type originally used in the EWTF, has been retired by its manufacturer.

Pywell (2007) also noted the steady development that led to the capable but limited threat simulators of the 1990's. This view is evidenced and supported by others: Morrow (1985), JED staff (1991; 1993), Smith and Taylor (1994), Herskovitz (1998), Ali (2002), McGahan (2002), **Pywell** and Midgley-Davies (2010), and Welch and **Pywell** (2012).

Chapter 5 will next expand on these developments, with particular focus on past and prospective improvements that could, theoretically, enable *all* RF EW receiver T&E to be conducted in ground-based facilities. This would cost-effectively enable flight testing of RF EW systems to be confirmatory in nature and would assist focus on RF EW tactics and countermeasure development, and aircrew training.

Chapter 5

DEVELOPMENT AND MANAGEMENT OF TECHNOLOGIES FOR HIGH-FIDELITY, MULTI-EMITTER RF THREAT SCENARIOS

5 DEVELOPMENT AND MANAGEMENT OF TECHNOLOGIES FOR HIGH-FIDELITY, MULTI-EMITTER RF THREAT SCENARIOS

5.1 INTRODUCTION

This chapter expands on technology development and utility of threat simulators for generating improved quality multi-emitter threat scenarios at RF for T&E of EW receivers. It describes two decades of developments that can enable more comprehensive evaluation of those systems than previously possible.

Section 5.2 covers the development of RF threat scenarios for use in EW T&E programmes, after first considering military and civilian emitters that appear in the air RF environment, and operationally realistic scenarios.

Section 5.3 covers threat simulator technology development methodology and discusses the definition of T&E equipment requirements for management of technology development. Whilst RF threat simulator technology has advanced significantly but expensively over the last two decades, there remains less than perfect correlation between flight test and ground test results. The resultant thorny question of how much more improvement is worthwhile and – as important – affordable is considered. The process for driving out technology development requirements is described and recent, as yet unpublished development of an affordability-driven threat simulator technology prioritisation assessment method is elaborated and its strengths and sensitivities outlined.

Section 5.4 lists technology developments, with indications of progress and the level of this author's contributions to driving out key development requirements.

Section 5.5 provides some closing remarks on this key chapter of the thesis.

This author's primary contributions have been twofold: 1) Development of specifications for high-end threat simulators for development and in-service support of ESM on world-class military aircraft; and 2) Driving, guiding and influencing selected threat simulator developments *via* aircraft projects, defence research and procurement agencies, sister aerospace companies, EW equipment suppliers and RF threat simulator suppliers. Appendix A contains a supporting letter from the world's foremost threat simulator company, Northrop Grumman Amherst Systems Inc.

5.2 DEVELOPMENT OF RF EMITTER SCENARIOS

RF threat simulators are required to produce adequate simulations of the RF characteristics of a range of threat and other emitters, singly or in multi-emitter scenarios, for the T&E of EW RF receiver systems. This section considers, as appropriate to this unclassified thesis, emitters and scenario types as relevant to typical test missions.

5.2.1 RF scenarios - military and civilian emitters

The air RF environment that a military air platform must fly through during combat operations and military operations other than war is complex and difficult to predict with any certainty (**Pywell**, 1996b; 2004), a situation that still prevails. The platform's RF EW receiver(s) must be able, as described in section 2.3, to detect, ID and DF radar-guided threat weapon systems that pose a clear and present danger to the platform, to enable optimal countermeasure employment, in the presence of this environment. This environment:

- Comprises the summation of electromagnetic waves from many RF emitters, military and civilian, which impinge on the platform's ESM antennas.
- Varies significantly with time as a function of many factors, *inter alia*:
  - Emitter speed (stationary, ground-mobile or airborne) and transmit characteristics, including antenna scan patterns.
  - Aircraft manoeuvre: pitch, roll and yaw and their rates; and longitudinal (speed and acceleration/deceleration), vertical and lateral movement.
  - Relative geometry between aircraft and each emitter (sight line angles and rates).

The types of RF emitters encountered in the air RF environment comprise:

- Military: hostile, friendly, neutral and own-side emitters.
- Civilian: *e.g.* Radio and TV stations; point-to-point microwave links; air traffic control; and mobile telephones and their base stations.

They are predominantly in the common radar EW frequency band, 0.5-40 GHz (Schleher, 1999, p.334; **Pywell**, 2007), with others outside this in the 20 MHz - 100 GHz range (United States. Department of Defense, 2011a).

5.2.2 Operationally realistic RF scenarios

In order to specify operationally effective EW RF receivers, consideration is made of operationally realistic RF scenarios. Operational analysts consider the operational environment and develop operational scenarios and vignettes[12], which describe key aspects appropriate to their intended use (Keppler, 2008; **Pywell**, 2010; **Pywell** and Midgley-Davies, 2010; Murray, Curtis and Pincombe, 2012; Young and Morley, 2012). These are usually produced by Defence Ministry agencies, such as UK MoD's Scenario Advisory Group (SAG), which generates operational scenarios and assumptions for studies, commonly known as 'SAG settings'. These are used by technical specialists to construct a series of operationally realistic RF emitter scenarios based on those settings. The emitter scenarios are then used to specify receiver system parameter ranges and performance requirements.

These scenarios are initially descriptive in nature, *e.g.* comprising threat weapon systems' laydown (placement) and behaviours (CONOPS, movements, radar mode changes) during the mission. They generally contain land, sea and air radar emitters, for hostile and own-side platforms, and usually include both sides' RF jammers. They are also commonly called 'threat scenarios' and, initially, may – for D&D, qualification and performance verification purposes - only contain military emitters (hostile, friendly and own radars and jammers). For MD and overall receiver performance validation, and for mission rehearsal operational problem investigation, they can also be populated with civilian emitters and include other factors, such as mission area terrain mapping.

Modelling is required to convert the above into a definitive Electronic Order of Battle (EOB), which details all known Blue (own-side) and Red (opposition) emitters and platforms in a given area of responsibility. It enables an understanding and time-line description of the air RF environment to be encountered during a given mission (Horne, 2000; **Pywell**, 2004; 2007; 2010).

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[12] Analysis of military campaigns can be described as containing three broad levels of detail: Scenario: strategic context for capability development planning. Vignette: plausible snapshot of an action during a scenario that is likely to comprise combinations of TTPs. TTP: Tactics, Techniques and Procedures: fine detail for military actions (Murray, Curtis and Pincombe, 2012).

Unfortunately, modern battlefield EOBs can present a complex picture (Horne, 2000), with multiple engagement zones for multiple threat weapon system radars. Each system usually comprises more than one individual radar, to cover the required functions of search, Target Tracking (TT), Fire Control (FC) and Missile Guidance (MG) and each of these have one or more different RF characteristics.

To complicate things further most have ill-defined scan pattern start times and their actual turn-on times and inter-mode transitions are often determined doctrinally rather than by the radar's optimum technical performance. For instance SAM operators will often hold off RF transmissions until the target aircraft is almost overhead, to minimise aircrew and DAS time available to react and counter a missile firing, as was the case for the 1995 F-16 shootdown mentioned in section 2.3.4. This tactic also minimises the radar's chance of being targeted by ARM from the inbound aircraft.

It is thus inevitably difficult, if not impossible, to arrive at a fully representative timeline definition of either the air RF environment for a given mission or the probability of exposure of one's own receiver antennas to emanations from threat and other emitters during that mission (Pywell and Stubley, 1995; Pywell, 1996b; **Pywell**, 2010). This presents a challenge to the specification of EW RF receivers and RF threat simulators alike and this is discussed in the next sub-section.

A key factor in the specification of RF threat simulators is maximum RF environment density capability, comprising CW and pulsed RF signals, at the digital level and, more importantly for SIL and ISTF use, _at RF_. This is generally measured in mega-pulses per second (MPPS) or kilo-pulses per second (kPPS), although this can be misleading when used as a single number to describe either an EW RF receiver's or a threat simulator's capability:

Pywell (1997) indicated pulse density for ESM systems is in the range 1-10 MPPS. More recently, Next Generation EW Environment Generator (NEWEG) indicates a maximum density of 8 MPPS (United States. Department of Defense, 2011a). EW RF receivers are specified, however, in MPPS *for a given bandwidth*, which is highly dependent on receiver architecture. For example, Kulkarni *et al.* (2013) compared digital receiver signal processing schemes as applied to current ESM/RWR systems. They reported that, for a 500 MHz bandwidth digital receiver, six out of seven processing schemes considered had maximum pulse density handling capability of 2 MPPS.

Whilst using a single MPPS figure is useful to indicate overall level of a threat simulator's capability, it does not provide sufficient information to cost-effectively specify the number of RF channels required to satisfy a specific level of test requirement. Simulator suppliers indicate each RF channel can generate 0.5-1.6 MPPS, although an only an average of ~0.3 MPPS per RF channel can be achieved for relatively simple real-world emitter scenarios. Some simulators also have a pulse 'burst mode' feature, giving above 10 MPPS, but this is not representative of real-world scenarios (**Pywell**, 2007).

From the above it can be seen that, to simulate a real-world RF environment with a scenario density of two MPPS over a given frequency range, then the simulator would need seven RF channels covering that same range – an appreciable cost-driver. This aspect is discussed further in section 5.3.

5.2.3 RF scenarios used in EW T&E programmes

RF scenarios used for T&E of RF EW receivers vary significantly dependent upon SUT capability and test requirement, the latter of which, in turn, is highly dependent upon test mission type (**Pywell**, 1997; 2007; **Pywell** and Midgley-Davies, 2010). Table 5-1 provides an insight into the multiplicity of RF emitter scenarios possible and indicates the complexity of determining what emitter scenario simulation capability is required of a RF threat simulator for T&E of a given SUT.

It is useful at this point to distinguish between so called 'clean air' testing and real-world operations where civilian emitters are always present and own/hostile jammers are often present. Much qualification and verification testing is generally done without these two emitter classes present in the scenario since:

- Jammers in particular are difficult to accurately simulate in ground-based T&E facilities. Of note is that most RFEGs are emitter generators, not explicitly ECM/jammer simulators, which require specialised sources not usually fitted to threat simulators (**Pywell** and Midgley-Davies, 2010, p.544).
- Inclusion of jammers and civilian emitters significantly complicates testing and subsequent analysis activities in most cases, with little overall benefit to the overall EW T&E programme. It has often been deemed more realistic and cost-effective to cover this part of the T&E envelope *via* flight test and trials on OARs. Technology developments in threat simulators and RMS since 2006 and those targeted by the NEWEG project (United States. Department of Defense, 2011a; 2011c) suggest that ground-based T&E facilities will be able to offer more in this area by end-2015.

TEST MISSION TYPE[13]		RF-LEVEL TESTING CAPABILITY					
		SINGLE EMITTER		MULTI-EMITTER			
Type	Example sub-type(s)	Scan motion		Number of military emitters		Mission rehearsal	
		Stationary	Included	Limited	Representative	Simulation	Emulation
Research and Development	• Design trade-off studies for new and upgraded receivers • Evaluation of receiver technologies • Investigation of de-interleaving techniques and algorithms	√	√	√	√		
Receiver sub-system development, integration and qualification	• System sensitivity • Minimum discernible signal • Response time assessment • Signal density handling	√	√	√			
Receiver performance verification	• DASS integration • Avionic systems integration • Platform systems integration • Flight testing	√	√	√	√	√	Future possibility
Receiver performance validation	• Operational evaluation trials • Mission Data validation • Tactics and countermeasures development	√	√	√	√	√	
In Service (Operational) Support	• Mission Data validation • Tactics and countermeasures optimisation • Problem evaluation and anomaly investigation	√	√	√	√	√	

Table 5-1: RF emitter scenarios typically utilised vs. test mission type

[13] A general list of EW test missions is given in **Pywell** (2007, p.534).

Some of the descriptors used in Table 5-1 are discussed and qualified below, as they are somewhat subjective and thus open to interpretation, given the lack of internationally agreed definitions.

- Limited number of military emitters: Limited number of military radar emitters, predominantly hostile ones, in a limited number of frequency bands and not always with all modes of each emitter.
- Representative number of military emitters: Operationally representative types and quantities of military radar emitters, in all SUT-relevant frequency bands, with all modes of each emitter.
- Mission Rehearsal (Simulation): Broadly representative number of military emitters, including jammers, each with medium to high level fidelity, and realistic platforms' motions. Broadly representative civilian emitter environment. Representative EOB, though not necessarily fully characterised or accurate, with limited account of the level of integration of the opposition's Air Defence System (ADS) in the theatre of operations the mission is to be conducted in. Limited modelling of terrain (roughness, multipath, line-of-sight obscuration), sea state and weather.
- Mission Rehearsal (Emulation): Realistic number of all emitter types in the mission's geographical area. Each emitter's simulation fidelity such that the receiver cannot distinguish between simulated RF waveforms and those from real such threat system's radar(s). Use of playback of measured RF environment data at the Pulse Descriptor Word and RF level (Anderson *et al.*, 2005; **Pywell**, 2007; **Pywell** and Midgley-Davies, 2010). Realistic platforms' motions and EOB, *i.e.* with intelligence-sourced, validated and preferably real-world-measured RF characteristics of emitter mode changes (Anderson *et al.*, 2005), taking into account the opposition's level of ADS (**Pywell**, 2004, p.457). Realistic multipath and RF propagation modelling for terrain, sea state and weather conditions for the mission's geographic location, season of year and time of day. Inter- and intra-platform multipath of electromagnetic energy from on-board and off-board emitters (**Pywell**, 2004; 2007; 2010; **Pywell** and Midgley-Davies, 2010).

Developments moving simulator capabilities toward the ideal 'Mission Rehearsal (Emulation)' level are discussed later in this chapter.

Whichever test mission is being executed, it is widely recognised that test quality and cost-effectiveness rely on using the highest available emitter and scenario simulation fidelity, and this is discussed in section 5.3. Care is needed by test designers and engineers to manage differences between this level of simulation fidelity and the best available understanding of the air RF environment for the SUT's platform's mission(s) to be undertaken. It should be noted that the full required range of tests for a given SUT cannot usually be performed at a single facility due to T&E equipment limitations. These limitations are usually affordability-driven and result in a SUT's qualification and V&V requirements being met *via* a combination of M&S, for the most complex and dense RF emitter scenarios (**Pywell**, 1997), and testing at a number of test facilities: SIL, HITL, MF, ISTF and OAR, the last of which generally covers the least dense RF emitter scenarios (Welch and **Pywell**, 2012, Ch.6).

Tools now exist to aid SUT designers and testers define, with appreciable accuracy and repeatability, RF emitter scenarios for testing. Examples include Interactive Scenario Builder (United States. Department of Defense, 2013) and the Environment Generation and Analysis (EGA) tool (Northrop Grumman, 2013a), a non-real time exact pulse-to-pulse simulation of CEESIM RF threat simulator hardware. Figure 5-1 shows a typical output from EGA.

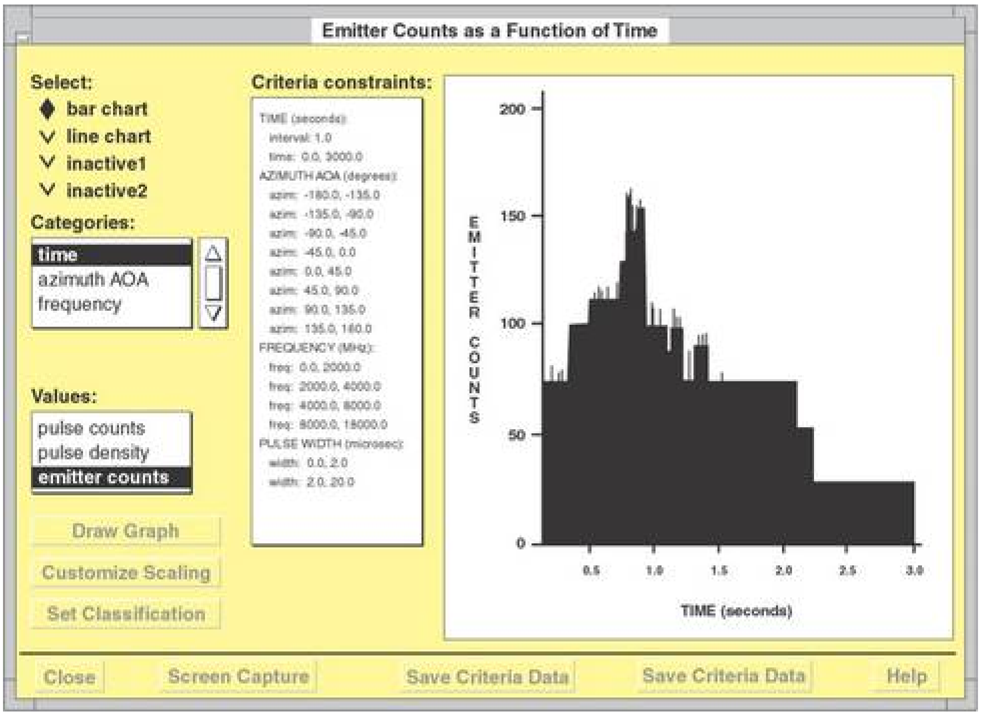

Figure 5-1: Typical EGA output

(With permission, © Northrop Grumman, Amherst Systems Inc.)

5.3 THREAT SIMULATOR TECHNOLOGY MANAGEMENT

This section provides an exposé of threat simulator technology management. It discusses threat simulator requirements definition and the management of technology development. The RF threat simulation community's age-old question, '*Simulation fidelity – what is enough?*', is discussed. The process is described for driving out technology development requirements for improved simulation of multi-emitter threat scenarios. Development of a new technology prioritisation assessment method is detailed.

This section draws heavily on '*Developments in RF simulator technology – approaching the affordable fidelity limit'* (**Pywell**, 2007), which was awarded a Silver Award from the UK's Royal Aeronautical Society (see Appendix A) and whose topic lies at the core of this thesis.

5.3.1 Defining requirements for managing technology development

For any EW RF receiver T&E programme necessitating the acquisition of a new RF threat simulator, it is necessary to define the function and performance[14] requirements set that is considered adequate for the test mission(s) to be undertaken, *cf.* Table 5-1. Similarly, technical specialists, engineering and technology managers, and project managers have a similar need to determine this requirements set for modification of an existing simulator to satisfy:

- those needs, or
- those pertinent to the T&E of an upgraded EW RF receiver system.

As indicated in section 1.1.2, this author has, over many years, fulfilled the above roles. He has developed requirements for and driven technology developments for a number of RF threat simulator acquisition and upgrade programmes, to support SUT T&E projects, *cf.* supporting letters in Appendix A.

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[14] Function is defined as 'What needs doing?' and performance is defined as 'How well does it need doing?' **Pywell** (2010) and an example is given in section 3.1 therein.

Whilst bespoke, limited capability threat simulators were originally the EW T&E mainstay for laboratory use before the late-1970s (**Pywell**, 2007), affordability considerations since have led to Tailored Off The Shelf (TOTS[15]) simulators now being the norm world-wide for SIL and ISTF use. In this TOTS case it is necessary to identify the delta in function and performance between the capabilities of a Commercial Off The Shelf (COTS) simulator and what is needed to adequately satisfy the SUT's planned T&E programme.

Most function and performance requirements can be derived relatively easily from the SUT's specification, *e.g.* frequency range. Others, however, are derived measures (Welch and **Pywell**, 2012), *e.g.* radar scan type and rates, and technical considerations are required to develop the range, accuracy, resolution and repeatability requirements of the underpinning parameters.

Section 5.3.3 explains the process of driving out technology development requirements for threat simulators. Whilst SUT test missions and threat simulator technical function and performance requirements are important and can lead to the need for technology developments, there are two other aspects that determine the eventual specification and any technology development requirements. These are lead times and affordability and are discussed here:

- Lead times: Long lead times for threat simulators and upgrades to them mean test requirements have to be defined well in advance of testing. For a high-MPPS modern simulator with (say) 7-11 RF channels (**Pywell**, 2007), this author's experience shows the lead time for a new simulator with a moderate amount of required technology development is in the region of 3-4 years from commence requirements capture and specification production to site acceptance testing completion and readiness for use in T&E activities.

  Lead times for a smaller (say) 4-channel system are in the region of 2-3 years. Lead times for upgrades depend upon the upgrade's scope. For example, software changes can range from 1-2 years and hardware upgrades or modifications from 1-3 years. This situation usually leads to some level of requirements set incompleteness, as the specification of the SUT or its upgrade is often not complete at the time that the threat simulator or simulator upgrade has to be contracted.

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[15] TOTS are also known as Modified (or Modifiable) Off The Shelf (MOTS).

This is consistent with others' experiences regarding EW T&E facility development, *e.g.* Olver, *et al*. (1992). When considering lead times for facilities to test new advanced technologies, they noted:

> *"Planning and administrative times average about 3.5 years with 1.5 years more in actual construction to acquire the required test capability." (Olver, et al., 1992, p.61).*

- Affordability: RF channels' number and types are dominant price drivers. To verify performance of a modern EW receiver and jammer system wholly by test a simulator would need many more RF channels than the current maximum of 24 (**Pywell**, 2007; Sabat, 2012; Welch and **Pywell**, 2012).

  For example, using the ~0.3 MPPS per RF channel stated in section 5.2.2 for simulating relatively simple real-world scenarios, a minimum of 27 channels would be needed to meet the highest known simulator requirement of 8 MPPS (United States. Department of Defense, 2011a). In reality, many more channels would be required as a large number would need to contain RF sources of the High Speed Synthesised (HSS) type, for simulating commonly encountered high Pulse Repetition Frequency (PRF), Pulse Doppler (PD) and CW radars. Unfortunately, each HSS channel can usually only simulate one such emitter at a time. This 'dedicating' or 'locking' a channel to an emitter thus prevents use of that channel's emitter multiplexing capability. Consequently a larger overall number of RF channels of would be required to attain a given MPPS level and this view is supported by the NEWEG project, which has a 'target' of 36 channels to meet an 8 MPPS 'target' scenario density requirement (United States. Department of Defence, 2011a).

  The high price of HSS-based RF channels often leads to a typical simulator only having one or two, with the rest usually being of the very capable, much less costly, but lower quality Digitally Tuned Oscillator (DTO) or Frequency-Locked Oscillator (FLO) types. A notable exception to this is the CEESIM at the US Air Force Flight Test Center's Benefield Anechoic Facility, which has a benchmark 21 HSS channels and 3 slow-tune synthesised channels, together covering the frequency range 0.1-18 GHz (Sabat, 2012; Welch and **Pywell**, 2012).

A mitigating and affordability-driven innovation regarding HSS, instigated and specified by this author, allows interchangeable wideband RF channels across simulators, providing – in the EWTF case – the ability to move up to 10 HSS channels from four RFEGs and two RMS into a single RFEG as required for specific tests (**Pywell** and Midgley-Davies, 2010).

Thus, invariably to date, threat simulators used in laboratories and anechoic chamber ISTFs have had some scenario density limitations, predominantly driven by affordability. For example the combination of test requirements, affordability and overall EW T&E programme VfM considerations usually limits threat simulator capability in practice to typically at least 1 MPPS for SIL testing and 1.5-2 MPPS for HITL/ISTF testing (Pywell and Stubley, 1995; Welch and **Pywell**, 2012). This is indicated in Figure 5-2, (**Pywell**, 2007; updated in **Pywell** and Midgley-Davies, 2010), which shows the outcome of this author's surveys of threat simulator capability, as measured by their number of channels and hence equivalent MPPS[16].

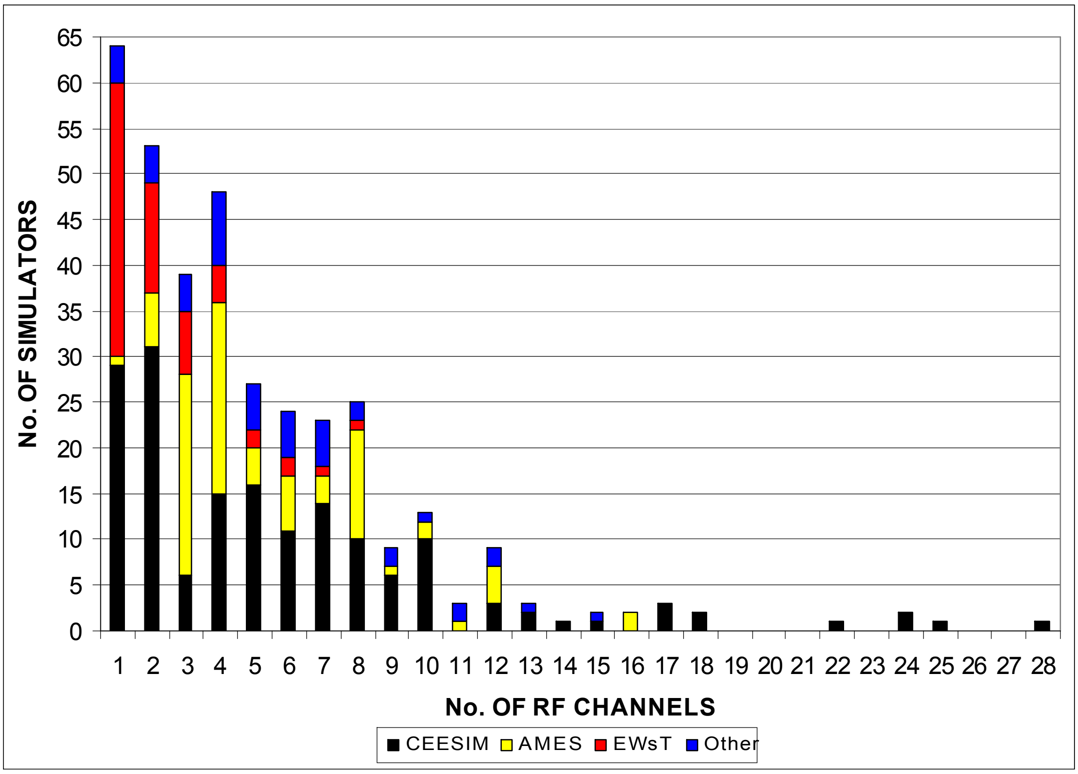

Figure 5-2: Scenario density capability – number of RF channels

[16] Whilst the number of RF channels has been a capability measure for more than two decades, the advent of wide-band channels, *e.g.* 2-18 GHz, means that a modern simulator can deliver the same MPPS capability with fewer channels than an older simulator. This author is exploring with simulator suppliers a better measure, likely a function of the number of channels in a given frequency sub-band and each channel's frequency range in GHz.

Figure 5-2 and its (proprietary, un-releasable) supporting information suggest typical use by facility type of SIL (≤8 channels), HITL (≤12 channels), and anechoic chamber ISTF (≥8 channels), all independent of channel type and frequency range (**Pywell**, 2007; **Pywell** and Midgley-Davies, 2010)[17].

Extrapolation of test results to full verification of receiver performance can be conducted *via* M&S (**Pywell**, 1997), although this is not yet a full substitute for the more comprehensive and robust verification by testing.

[17] The maximum verified number is 24 and the two higher figures are reported but not verified.

5.3.2 Simulation fidelity – what is 'enough'?

This section discusses RF threat emitter and scenario fidelity and the fundamental question '*What is enough?*' for adequate T&E of EW RF receivers. Section 5 of **Pywell** (2007) provides a detailed discussion of the topic, commencing with definitions of relevant terms and outline of simulator output validation and accreditation, before discussing the reasons for seeking higher fidelity RF emitter simulation, exploring the affordability boundary and suggesting further simulator technology developments.

Threat simulator output validation is the two-fold process of determining whether a) the simulator's output, when programmed with threat emitter models, is adequate for its intended use in the EW T&E process; and b) the SUT, when programmed with MD, correctly identifies and reacts to the simulated threat as if it were real. Accreditation is the process of determining whether a simulator's rendition of threat emitters is suitably realistic, robust and credible (**Pywell**, 2007). Validation and accreditation are not discussed here as they are adequately covered in **Pywell** (2007, p.558) and elsewhere (Hall, 2009; Stone, Bryson and Scarborough, 2009; Welch and **Pywell**, 2012, Ch.7) and do not directly impact on the technology development topic of this thesis.

The definitions in **Pywell** (2007) were required as a number of ill-defined and poorly quantified terms were and are still used world-wide, *e.g.* model, emulation/emulator, simulation/simulator, surrogate, replication/replicate and hybrid representation. Roza (2005) commented on this aspect:

> *"There exist many definitions for fidelity related terminology and almost every publication on modeling and simulation provides its own definitions." (Roza, 2005, p.261).*

These terminology differences exist when discussing the threat simulation fidelity topic with agencies within one's own country and across nations and are thought likely to persist. For example, Stepp (2007), Albert (2011) and United States. Department of Defense (2012a) refer to threat 'simulators', 'surrogates' and 'actual systems' providing a 'threat-rich environment' at the ECR at China Lake, California. Welch and **Pywell** (2012) also contains an ECR-provided Annex A input that refers to 'advanced threat simulations'.

A suitably general definition of 'fidelity' is given in the US DoD's M&S Glossary:

> *"1. The identification of key parameters for a system and the degree to which the aggregate of those parameters match a baseline system. The components of fidelity include functional, physical, psychological, tactile, visual, and wallpaper.*
>
> *2. The degree to which the representation within a simulation is similar to a real-world object, feature, or condition in a measurable or perceived manner.*
>
> *3. The accuracy of the representation when compared to the real world.The accuracy of the representation when compared to the real world." (USA. Department of Defense, 2011b, p.102).*

Whilst this thesis focuses on RF threat simulators of the type generally used in laboratories and anechoic chamber ISTFs, it is worthwhile addressing the similarly-applicable fidelity topic as relevant to OAR threat simulation. Martin (2005), of the US Army's Target Management Office (TMO), discusses the provision of mobile ground targets, including threat weapon systems such as SAMs and AAA, for joint service EW T&E. Martin defines surrogates as follows and usefully sub-classifies them as shown in Table 5-2.

> *"A surrogate, as defined by TMO, is any target with less capability than an actual threat." (Martin, 2005, p.8).*

Sub-classification	Level of simulation fidelity	Cost ($k)
Representative	Meets only select signature characteristics and has little or no mobility or operational capability of threat.	10-50
Moderately representative	Meets two or more signature characteristics of threat and emulates many of the threat's mobility/operational characteristics.	50-200
Highly Representative	Meets all realms of signature characteristics of threat and emulates all or most of the threat's mobility/operational characteristics.	≥200

Table 5-2: Surrogate sub-classifications

(Martin, 2009, p.8)

Martin (2005, p.9) also gives a range of costs vs. simulation fidelity for an example threat, the ZSU-23/4 AAA system (*cf.* **Pywell**, 2004, Figure 3): $2M for a real system and $15-100k for increasing surrogate capability.

This indicates the prohibitive costs of populating OARs with operationally representative numbers of threats, a major OAR limitation (Gilmore, 2011; **Pywell** and Midgley-Davies, 2010; Wallace, 2010; Welch and **Pywell**, 2012). It also illustrates a key EW T&E capability discriminator between OARs and SIL/ISTF threat simulators – the latter can simulate operationally representative number of emitters at the digital level and, subject to the simulator's number of RF channels, can do the same at RF **(Pywell**, 2007; Sabat, 2012).

There is consensus concerning key points regarding threats and simulations used for OAR T&E, as listed below (Martin, 2005; **Pywell** and Midgley-Davies, 2010; Wallace, 2010; Gilmore, 2011; Welch and **Pywell**, 2012, p.6-21).

- Actual threats meet all fidelity requirements and are preferred by aircrew for training 'as the next best thing to war' as the full range of tactics and countermeasures can be explored, including dynamic closed-loop effectiveness testing against threats.
- Actual threats have the highest acquisition and operating costs. Relative cost[18] and difficulty of fielding actual threat systems to support T&E programmes limits OAR testing value to the qualification and V&V process.
- OAR threat densities and mixes are, for affordability reasons, usually very limited compared to war. A mix of actual threat systems and surrogates (emulators and simulators) is usually the only affordable capability solution.

Pywell (2007) noted that threat simulation fidelity is dominated by two factors, which are applicable to simulators as used in any T&E facility type:

- threat emitters' characteristics programmed into the simulator, which is a function of quality of intelligence gathered on threat radar systems' technical attributes and operational use, as done for ECM MD, *cf.* section 2.3.3.
- 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. This is highly dependent upon SUT capabilities, T&E phase (DT&E, OT&E, V&V) and test mission, *cf.* Table 5-1.

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[18] The example actual-to-surrogate threat cost ratio examples in Martin (2005) are at worst 200:1, indicating a significant cost-benefit trade to be made when considering what tests and trials can be cost-effectively conducted on an OAR compared to in a SIL or anechoic ISTF.

The original question therefore is not a single question but is many-faceted with no single answer (**Pywell**, 2007). To further complicate matters, it is difficult to determine who should identify the level of simulation fidelity required for a given test mission and SUT (Anderson *et al.*, 2005; **Pywell**, 2007).

Anderson *et al.* (2005) suggested gathering fidelity inputs from customers, to minimise the risk of over- or under-specifying threat simulation fidelity. During a 2008 visit to their facility, this author discussed this suggestion with the agency which produced Anderson *et al.* (2005) and concluded, from mutual experience, that platform SUT customers are not likely the source of such fidelity quantification inputs; rather such inputs would likely come from a combination of EW T&E experts and RF threat simulator specialists.

There is good agreement on the topic of what simulation level is required and how RF threat simulation needs enhancement to enable closer correlation between ground-based and flight testing, which would enable the optimum amount of testing to be best achieved *via* ground testing. This is indicated in the following list, aggregated from Anderson *et al.* (2005), Stone, Bryson and Scarborough (2006), Grenier and Felsinger (2009), Hansen (2011), **Pywell** (2007), Welch and **Pywell** (2012, Chapter 7), and United States. Department of Defense, (2000; 2012b, pp.314-5):

- For T&E and training, RF threat simulation must be good enough to prevent data inaccuracies, anomalous EW displays and incorrect EW/DAS actions.
- RF threat simulators need to be credible and fit for purpose, *i.e.* good enough such that, for the test in question, the SUT cannot tell the difference between the simulator and an actual emitter's RF signals.
- For EW T&E, RF threat simulation must provide post-antenna injection signal strength, accuracy and other RF characteristics above the SUT's perception threshold.
- Fidelity needs to characterised in terms of resolution, error/accuracy, sensitivity, precision and capacity, as peculiar to the SUT in question.
- Need to constrain required and implemented fidelity to that required for specific T&E requirements – need to avoid over-design and 'gold plating'.

- There is likely a level of simulator fidelity beyond the enhancements identified in Anderson *et al.* (2005), **Pywell** (2007) and **Pywell** and Midgley-Davies (2010), not yet reached, where it will likely become more cost- and time-effective to flight test the SUT rather than invest further in enhancing ground-based T&E capabilities (**Pywell** and Midgley-Davies, 2010; Hansen, 2011, p.74).

Anderson *et al.* (2005), Stone, Bryson and Scarborough (2006), **Pywell** (2007), **Pywell** and Midgley-Davies (2010), and United States. Department of Defense (2012b, pp.314-5) concur on the need for higher-fidelity simulation capability to enable closer correlation between and across ground-based T&E facilities (SIL/HITL/ISTF) and between ground and flight testing, to enable more confidence in ground-based T&E facilities and reduce overall EW T&E costs.

Whilst the last two decades has seen a significant, albeit expensive, increase in the ability to generate multi-emitter threat scenarios for laboratory and anechoic chamber testing, there remains a substantial gap between the simulation of the air RF environment currently achievable with multi-£M threat simulators and that experienced in real-world RF scenarios flown by military aircraft (**Pywell**, 2007; **Pywell** and Midgley-Davies, 2010; United States. Department of Defense, 2012b, pp.314-5). Substantial efforts in the USA commenced in 2008 to address the above *via* the US DoD's NEWEG project (Gilmore, 2011; United States. Department of Defense, 2012b, p.314;Haystead, 2013):

> *"…the DoD requires a higher fidelity stimulation capability and closer correlation between ground testing and flight testing. Higher fidelity stimulation capability will further reduce overall test costs, reduce EW programme cost and risk via earlier detection of problems, and allow greater reliance on ground test results." (United States, Department of Defense, 2011c).*

The technical objective of NEWEG is to evolve the state-of-the-art in EW simulation and stimulation technology into much higher-fidelity threat signal simulation (United States. Department of Defense, 2012b), which supports the case made for multi-emitter RF scenario simulation enhancements proposed in **Pywell** (2007) and **Pywell** and Midgley-Davies (2010). Given the NEWEG project's high relevance to the topic of this thesis, relevant aspects are discussed further in section 5.4.

5.3.3 Driving out technology development requirements

This section describes the process for driving out threat simulator technology development requirements for improved simulation of multi-emitter threat scenarios. As necessary, some of this description is constrained by proprietary and security constraints applicable to this unclassified and public release thesis.

Figure 5-3 shows the generalised process for driving out threat simulator technology development requirements, which has been developed by this author and his EW Specialist colleague M. Midgley-Davies, and used by them and others since the early 1990's. It has been used to provide adequate T&E capability for these test missions for modern RWR, ESM and ECM: equipment qualification, sub-system development, avionic systems integration, installed performance verification, mission data validation and problem evaluation.

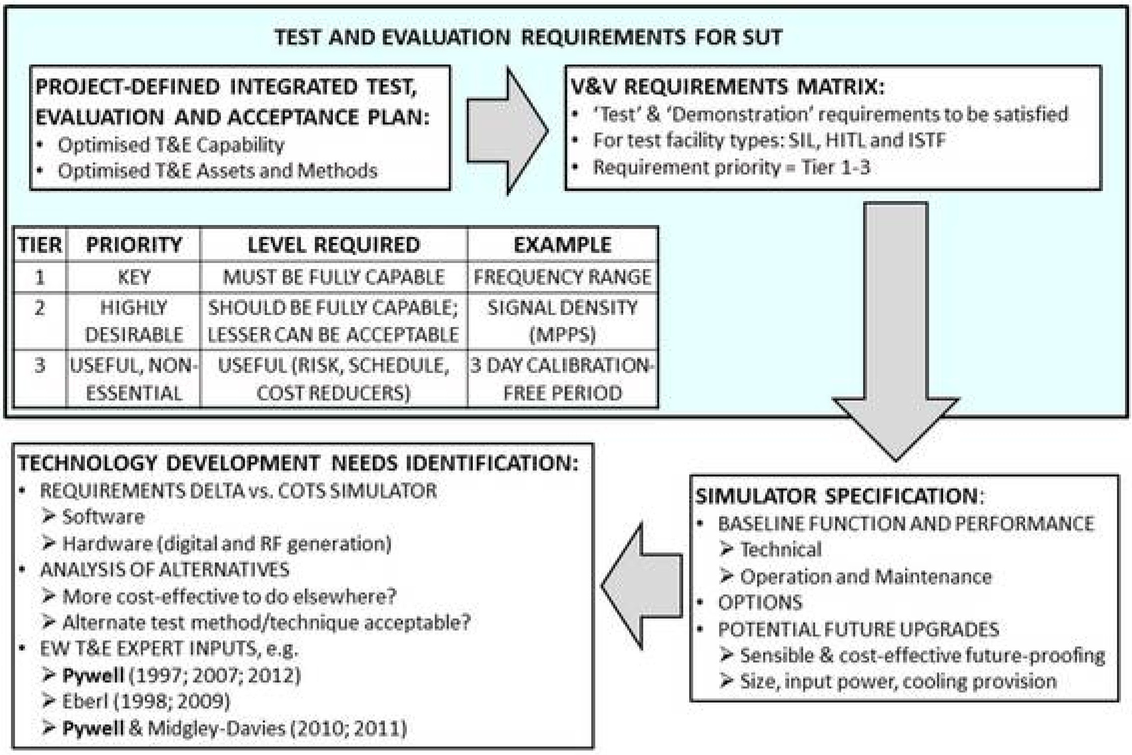

Figure 5-3: Simulator technology development identification process

The process for determining the T&E requirements needing to be satisfied using threat simulators on specific ground-based EW T&E facility types is described in **Pywell** (2010). Whilst the requirement priorities ('Tiers') in Figure 5-3 are not generally agreed, with national, military and industry differences, most known schemes have similar priorities.

To enable comparison of decomposed T&E requirements *vs.* the capabilities of COTS simulators, Pywell, sometimes assisted by his colleague Midgley-Davies, conducted a number of (unpublished) market surveys since the early 1990's, with focus on many-channel RF threat simulators (**Pywell**, 2007). These surveys have included questionnaires to suppliers, face-to-face interviews, information gleaned from open-source marketing material and supplier web pages, *e.g.* Northrop Grumman Amherst Systems (2013b) and EW Simulation Technology (2013), and other literature searching. The outputs of similar surveys *inter alia* those by JED Staff (1993), Herskovitz (1998), McGahan (2002) and Holt (2010) were included in those by Pywell and Midgley-Davies.

These surveys enabled determination of lowest common denominator function and performance of COTS threat simulators which were potentially suitable for testing a modern ESM-ECM. Comparison of this with the SUT specification and project-defined testing requirements enabled two lists:

- simulator modifications required to interface correctly with the SUT, primarily to the platform's EW receiver and ECM antennas; and
- key technology enhancements required to the COTS simulator's RF, digital and software modelling capabilities; some affecting multi-emitter simulation fidelity and others affecting other technical features or operation and maintenance aspects.

Development needs identified from the above and from simulation fidelity investigations conducted or directed by Pywell have ranged from simple lists of topic headings to more detailed, specific requirements (**Pywell**, 1997; 2007; 2012; **Pywell** and Midgley-Davies, 2010; 2011). These investigations highlighted which potentially worthwhile simulation capability improvements were and are more important than others to the production of adequate fidelity, multi-emitter threat scenarios.

Section 5.3.4 will next describe the development and use of a comprehensive technology prioritisation method for assessing the relative benefits of the wide range of potential development candidates considered.

Section 5.4 will then discuss specific technology development requirements and two decades of progress, and indicate the level of this author's contributions to driving out key development requirements.

5.3.4 Technology prioritisation assessment

This section describes the development of a detailed assessment method for prioritising dissimilar potential technology enhancements to RF threat simulators and ECM RMS for use in SILs, HITL facilities and anechoic chamber ISTFs. The method was developed to aid investment decision making *via* broadly objective assessments of relative VfM of a range of potential technology enhancements to these high value EW T&E equipment.

Whilst affordability of T&E capabilities has always been a key factor in the defence industry, the emphasis greatly increased in the years following the mid-2000's start of the world financial crisis (Great Britain, Ministry of Defence, 2008; **Pywell** and Midgley-Davies, 2010). Against this background and consequently diminished national defence budgets, affordability of all aspects of military air platform research, development, production and through-life in-service support became crucial to continued company survival in the face of fierce international competition. This resulted in a marked shift towards meeting today's and tomorrow's military objectives at minimum through-life cost – both fiscal and aircrew (**Pywell** and Midgley-Davies, 2010). Indeed, UK MoD's vision for its T&E capability is stated as "*Cost-effective accurate assessment of military capability through-life*" (Great Britain, Department of Defence, 2008).

When decomposed to the T&E capability and facility level, this now results in detailed assessment of any proposed acquisition's through-life cost and VfM, not just its acquisition price. In the high-value EW T&E equipment arena, this author, with support from his co-author colleague M. Midgley-Davies, developed during 2010-11 a rigorous method for evaluating the relative technical and VfM benefits of a number of possible enhancements to the RF threat simulator and RMS types used at his division.

The method was presented at the 2011 CEESIM User Review Meeting (Pywell and Midgley-Davies, 2011) to military T&E specialist users of threat simulators and emitter modellers, the threat simulator supplier (who invited the presentation, see supporting letter at Appendix A) and other simulator users.

The method and its development will now be described, with discussion of the per-candidate scoring process and weightings used in cost-independent and cost-benefit evaluations that were used to derive the final relative VfM of each of the technology development candidates considered. All but the bubble diagrams (Figures 5-7 and 5-8), showing a 'public release' example of the assessment tool's output, have been developed from the unpublished Pywell and Midgley-Davies (2011) presentation.

Figure 5-4 indicates the wide range of information sources investigated to arrive at the list of technology development candidates. The forward look window was 10 years, *i.e.* to the end of the 10-11 year useful life of a typical simulator (**Pywell** and Midgley-Davies, 2010; Haystead, 2013).

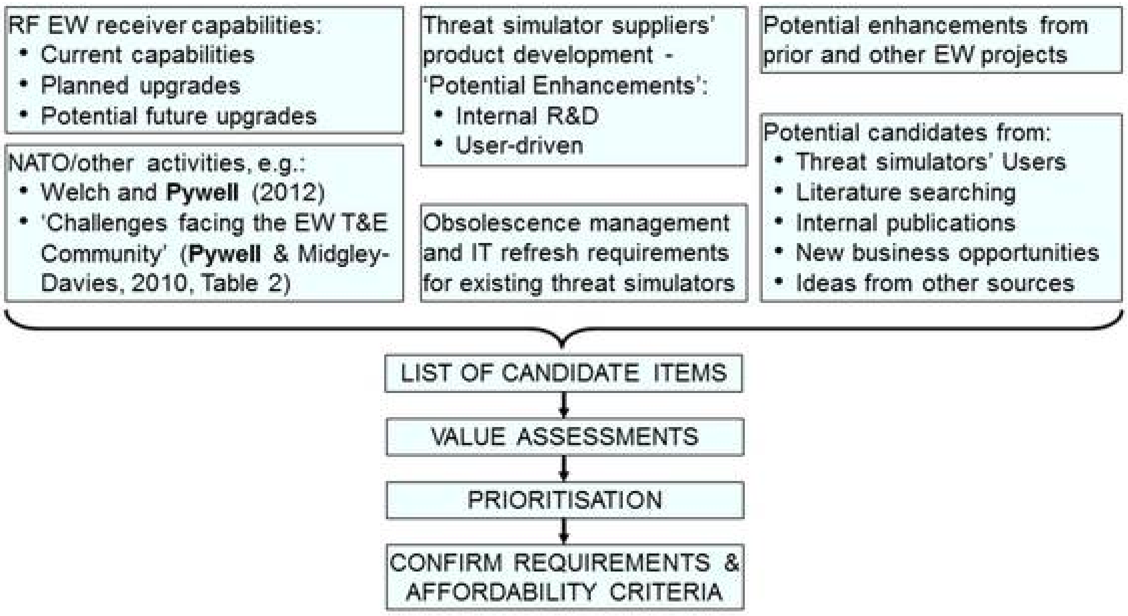

Figure 5-4: Derivation of threat simulator potential upgrade candidates

All known firm, probable, aspirational and speculative candidate justifications were considered. The initial total number of candidates, across threat simulator and RMS, was 120, although it was recognised that this was unlikely to be complete for two reasons: incomplete capture of all other users' views, and (then) currently unknown future SUT developments. The prioritisation method developed allows for easy additions to the list as required.

Once duplication and overlap had been accounted for, the total number of candidates reduced to 56, 29 for threat simulators and 27 for RMS. Overlap was the result of probable practical implementation of some upgrades covering more than one of the initial candidates.

Figure 5-5 is a block diagram indicating the development and use of the prioritisation method and process.

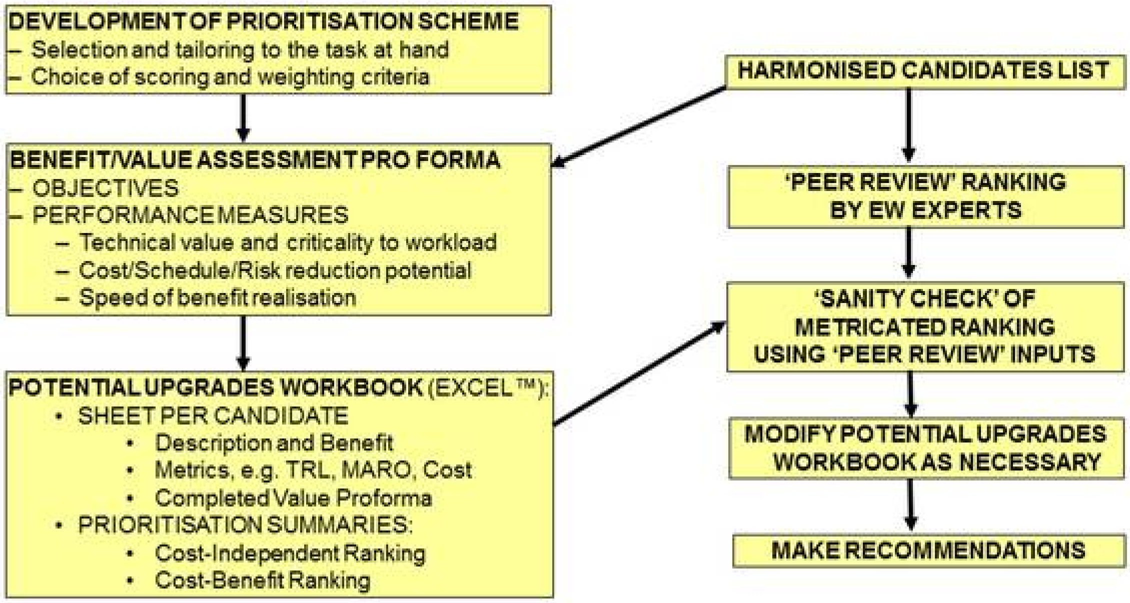

Figure 5-5: Assessment and prioritisation process

Many schemes exist for quantifying value and benefit, although all need tailoring to the subject under investigation (Merkofer, 2013). In this context value is defined as "*relative worth, merit or importance*" and benefit as "*something that is advantageous or good; an advantage"* (Dictionary.com, 2013). Both aspects were considered, although, within the scope of the process developed, the terms were interchangeable.

Clear objectives and performance measures needed to be identified for generating the benefit/value pro forma used to evaluate each candidate technology development. This entailed identification of key drivers for optimising EW T&E: those relating to the EW T&E process itself and those relating to the sustainment and appropriate development of EW T&E facilities and their T&E assets. The key word is 'appropriate' as there can be significant cost, time and risk impact of treating each potential development candidate in isolation. In practice, substantial cost benefit can be accrued by 'batching' candidates into upgrade packages. Within the scope of the investigations supporting the method development it was not possible to factor this into the prioritisation process developed as it was unrealistic to attempt to gather cost information for such a large number of permutations of candidates.

The assessment pro forma developed was based on Table 2 of **Pywell** and Midgley-Davies (2010), which proposed areas where the EW T&E community could enable or contribute to challenge[19] solutions. Other schemes are similar, with Brown and Babilon (2008) being a particularly relevant example, describing the prioritisation process used by the USAF for supporting their T&E roadmap.

This type of process is usually iterative, as the assessment is often only valid for a relatively short period after it is conducted due to changing input parameters, and typically covers:

- Capability objectives
- Gap analysis and prioritisation
- Facility uniqueness (cost/technical/risk impact of alternatives, if any)
- Support to customer base
- Identification and prioritisation of solutions
- Affordability considerations

The prioritisation process developed is equally applicable to a single item of EW T&E equipment, a EW T&E system such as a combined RFEG and RMS as used in the EWTF, or an overall T&E capability[20]. The prioritisation reported in **Pywell** and Midgley-Davies (2011) covered a time synchronised RFEG and RMS T&E system, as they were investigating the relative VfM of potential enhancements across those equipment. The assessment tool can allow the RFEG and RMS technology candidates to be ranked separately.

Table 5-3 is an abbreviated version of the assessment pro forma developed; it has been necessarily sanitised for this thesis – there are another four sub-objectives in the full pro forma.

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[19] Section 4 of **Pywell** and Midgley-Davies (2010) identifies a number of current and future challenges facing industry, defence procurement agencies and military end users in their quest to meet operational requirements at minimum whole-life cost.

[20] A T&E capability, as defined in the Defence Industry Strategy (Great Britain. Ministry of Defence, 2006), 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.

	OBJECTIVES	SELECTED PERFORMANCE MEASURES					
		Technical value & criticality	Cost reduction potential	Schedule reduction potential	Risk reduction potential	Speed of benefit realisation	Sub-total Value (by Objective)
1.0	**CAPABILITY SUSTAINMENT: Optimisation, Development and Sustainment of EW T&E Facilities**						
1.1	**Improve laboratory and chamber test capability robustness** - Trap more problems prior to flight, saving T&E cost/time by reducing number of fly-fix-fly iterations required - Better support R&D, evaluation of prototype technical solutions and EW Technology Demonstrator Programmes - Generate more operationally realistic and measurable threat environments for laboratory/chamber use	1	0	0	3	7	**2.00**
1.2	**Perform DASS T&E faster, more cost effectively and with less risk of test errors necessitating re-tests** - Useability enhancements to test equipment and facilities, also targeting reduced reliance on access to DASS/EW Specialists	9	3	1	1	3	**4.40**
1.3	**Enhance operational support** - Improve Mission Data Validation quality by generation and use of 'mission rehearsal' quality RF emitters and scenarios	7	0	0	7	3	**3.40**
1.4	**Reduce number of iterations of SS Rig, SI Rig, EWTF chamber and aircraft ground/flight trials** before the - DASS and its upgrades reach the required level of product maturity - level of performance verification to achieve contract sign-off has been achieved	1	0	1	3	7	**2.10**
1.5	**Increase Availability of T&E facilities and capabilities** to service the needs of DASS test programmes	3	1	3	1	7	**3.00**
1.6	**Support networking of UK DASS/EW T&E, Synthetic Environment and Modelling & Simulation facilities to**	0	0	0	0	0	**0.00**
1.7	**Assure DASS/EW laboratory and EWTF capability sustainment**	3	1	1	3	3	**2.20**
1.8	**Enable maximum transfer of testing from flight to ground to chamber to rig to validated modelling &**	7	0	1	1	3	**2.90**
1.9	**Enable closer cooperation between key UK DASS/EW T&E assets**	1	1	0	1	3	**1.30**
2.0	**TIMELY DEFINITION/ACQUISITION OF CAPABILITY FOR T&E OF DASS UPGRADES**						
2.1	**Planned upgrades** (where 'planned' means 'current view agreed with relevant Project')	3	1	1	7	3	**2.60**
2.2	**Potential Future Upgrades**	7	0	0	7	1	**3.00**
3.0	**INCREASED DASS PROJECT SUCCESS PROBABILITY: via reduced timescales, cost and risk**						
3.1	**Rapid Development, Insertion and Acceptance of DASS changes/improvements/problem fixes**	3	0	1	1	1	**1.30**
3.2	**Reduced Cost and Environmental Impact of DASS/EW T&E and Facilities**	1	3	1	3	7	**3.00**
3.3	**Reduced Platform Through-Life Risk associated with DASS T&E and Facilities**	3	0	1	1	3	**1.70**
4.0	**EW BUSINESS DEVELOPMENT**						
4.1	**Enable/Capture/Develop new business**	3	0	1	1	3	**1.70**
	Sub-total value (by Selected Performance Measure)	**15.60**	**3.00**	**1.20**	**4.00**	**10.80**	
						TOTAL VALUE	**34.60**

Table 5-3: Assessment pro forma for technology upgrade candidates

The objectives and sub-objectives were tailored by a number of things including test missions to be conducted and overall T&E strategy. Each sub-objective has a number of guide phrases to assist the scoring process. To fit the pro forma at Table 5-3 legibly on one page, all but seven of the 50 such guide phrases have been removed. The first objective, 1.0, indicates the types of guide phrases. The maximum score for any candidate, based on the full pro forma and weightings applied is 171.

Table 5-4 shows the choice of scores and weightings used by Pywell and Midgley-Davies (2011). The benefit scoring scheme developed is a variant of R&D project prioritisation schemes and enables the discrimination of many disparate items with very similar benefit and value.

SCORING - BENEFIT				
Major	Significant	Moderate: approx. half of 'Major'	Minor	None or N/A
9	7	3	1	0
SCORING - SPEED OF BENEFIT REALISATION (MONTHS)				
0-6 months	7-12 months	13-18 months	19-24 months	>24 months
9	7	3	1	0
WEIGHTING vs. SELECTED PERFORMANCE MEASURES				
Technical value & criticality	Cost reduction potential	Schedule reduction potential	Risk reduction potential	Speed of benefit realisation
30%	30%	10%	10%	20%

Table 5-4: Choice of scores and weightings

The ‘speed of benefit realisation’ months’ bandings match typical upgrade implementation times, including site integration and acceptance time. Pywell and Midgley-Davies (2011) considered seven weighting schemes for the selected performance measures shown in Table 5-3, with those in Table 5-4 resulting from a balance between significant benefit (‘big hitter’) and rapidity of benefit realisation (‘quick win’). The authors elected not to apply weightings to the objectives in Table 5-3 as it was considered too complex a consideration within the time and funding available and was thought unlikely to majorly affect the resultant candidate prioritisation.

Once the assessment method had been developed, the process followed by the investigators, Pywell and Midgley-Davies, was:

- Technology candidate scoring. Pywell, as threat simulator technical lead conducted this for RFEG candidates and Midgley-Davies, as RMS technical lead, conducted this for that equipment. The range of scores was 7.7 to 78.8 which, as the maximum per candidate score was 171, counter-intuitively suggested than none of the candidates were particularly worthwhile. As more than a quarter of the candidates are known to be of high relevance and/or value to test missions and planned SUT upgrades, further investigation is warranted of the assessment pro forma content and choice of scores and weightings (Table 5-4).
- Generation of initially prioritised lists. Each candidate's score was entered into two spreadsheets, one ranking candidates independent of their costs, the other using each candidate's indicative cost to give cost-benefit ranking.
- Management of assessment subjectivity. There was a clear need for this management given the nature of the task, a time- and funding-limited investigation with few firm input requirements; no ratified costs and implementation timescales; and extremely limited access to supplier technical and project management information. The bias reduction method chosen by this author was a 'Peer consensus ranking review', a type of Delphi review (Merkofer, 2013), constrained to three RFEG and RMS experts, Pywell, Midgley-Davies and C. Sims, all of BAE SYSTEMS. In isolation each reviewed the 56 candidates, performing a brief relative ranking based on their experience and view of future EW T&E activities, thus yielding three subjective, but expert, prioritised rankings. These were then compared to the cost-independent ranking produced earlier.

  Differences between the four rankings were investigated resulting in:

  - Harmonious view of 14 candidates' rankings. Lesser agreement, reasons for which were subsequently understood, leading to eventual agreement on 21 candidates' rankings.
  - 4 candidates' rankings were highly suspect, with all three experts substantially disagreeing with the ranking based on candidate's initial scores. These were consensually re-scored and re-ranked.

- Re-scoring of 17 candidates in the light of the expert consensus. Some were, in hindsight, considered to have been outset mis-scored. The remainder were considered due to no single individual having a complete view of current and future EW T&E requirements, capability limitations and test equipment technology upgrade potential.
- Generation of final cost-independent and cost-benefit rankings. For proprietary reasons these cannot be presented in this thesis.

- Final output of prioritisation: To arrive at a final prioritisation the method chosen was to map each candidate's cost-independent score against its cost-benefit score on a 'bubble diagram', as depicted in Figure 5-6. This is an adaptation of a method in widespread use for helping decision makers, with examples including investment prioritisation of R&D projects and business portfolios (Pywell, 2006; Merkofer, 2013).

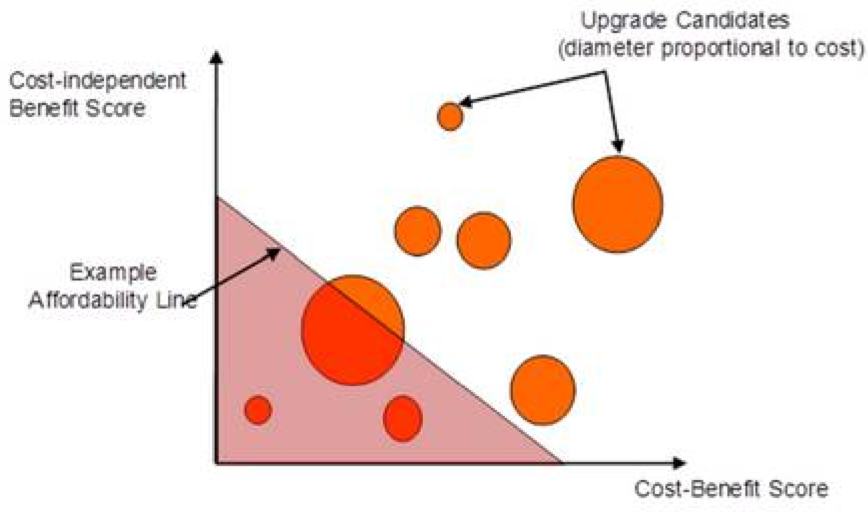

Figure 5-6: Schematic output of prioritisation tool

Figures 5-7 and 5-8 show actual outputs from the prioritisation tool, with sensitive information removed. The tool is an Adobe ActionScript® Shockwave flash application[21] in Microsoft Excel™ in the technology upgrades assessment workbook. Figure 5-7 shows logarithm_{10} (cost) of each upgrade *via* its circle's radius, but this makes inter-candidate visual discrimination difficult, whereas Figure 5-8, which has circle radius proportional to cost, clearly separates all the candidates, also indicating by how much a candidate's scoring would need to change before its position in the ranking would be changed.

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[21] This was produced by colleague A. Petrus under the direction of this author.

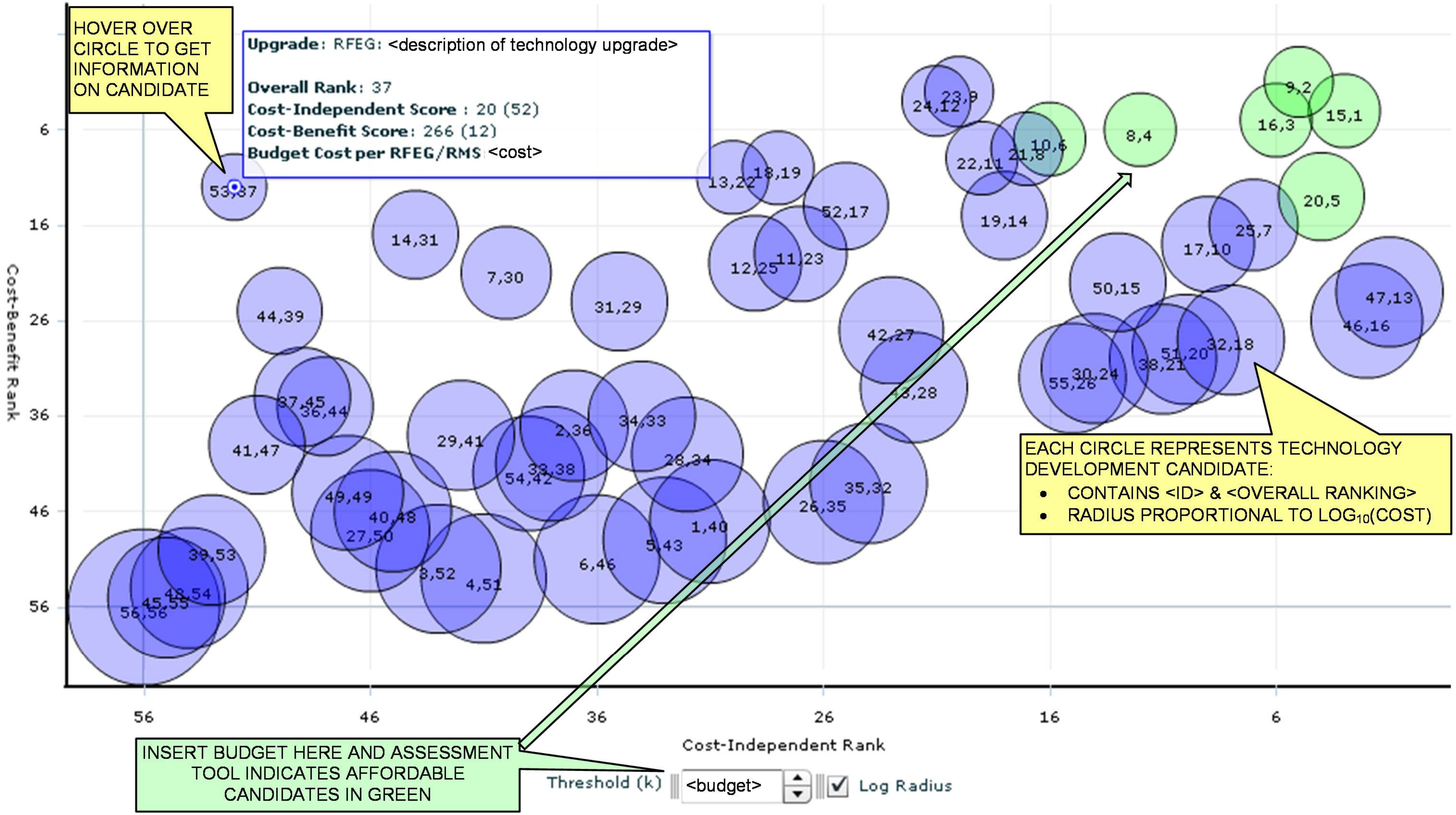


Figure 5-7: Example output of prioritisation tool (1)

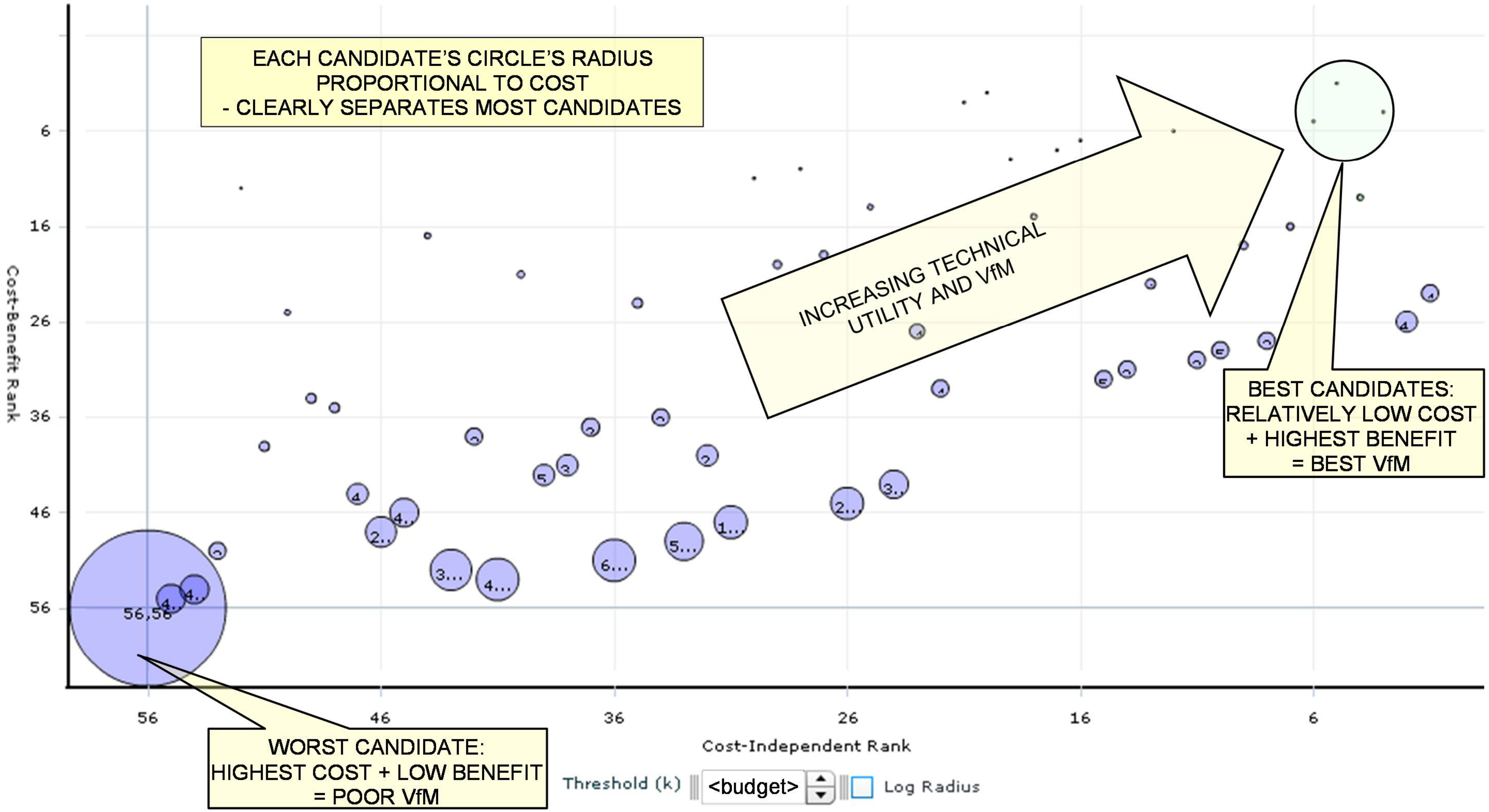


Figure 5-8: Example output of prioritisation tool (2)

The following closing remarks are made on development of this method for affordability-driven simulator enhancement priority assessment.

- The development has been described of a detailed assessment method for prioritising dissimilar potential technology enhancements to RF threat simulators and ECM RMS for use in SILs, HITL facilities and anechoic chamber ISTFs.
- The method was developed to aid investment decision making and, although somewhat subjective, the outcome's sensitivity to that subjectivity is considered to have been adequately managed. Management quality could be enhanced by the inclusion of more subject matter experts.
- Assessment outcome time sensitivity for a given set of candidates cannot be managed other than by periodic update of the candidates' scoring against the selected performance measures, and review and update of the benefit metrication method and weightings. There is merit in exploring the reasons behind the apparently low range of scores determined by Pywell and Midgley-Davies, 7.7 to 78.8 compared with a theoretical maximum of 171, which may suggest the need for benefit assessment method optimisation.
- The time- and funding-limited investigations by Pywell and Midgley-Davies (2011) only allowed assessment using an initial view of each technology upgrade's acquisition cost. A more robust assessment would need formal supplier's prices and should include whole-life costs, *i.e.* acquisition cost plus in-service support costs over the equipment's useful life. A suggested future research activity would be expansion of the bubble diagram assessment tool to include the effects of acquisition and in-service support costs. The development of a three-dimensional bubble diagram to enable visualisation of both this whole life cost impact and effects of upgrades 'batching' would appear to have merit.

5.4 TWO DECADES OF PROGRESS IN SIMULATOR TECHNOLOGY DEVELOPMENTS

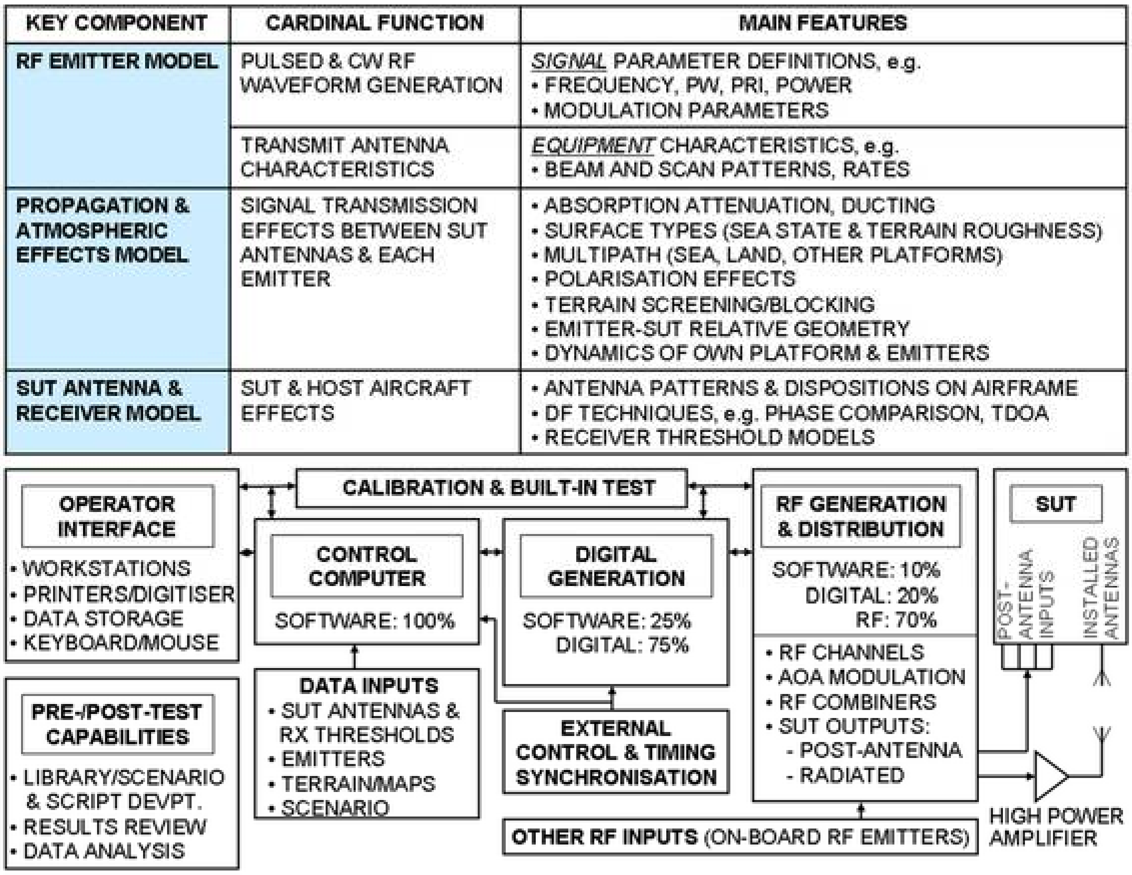
This section identifies technology developments since the mid-1980's that have improved the capability and availability of RF threat simulators to support multi-emitter scenario testing of EW receiver and jammer systems. The level of contribution of this author to the specification and implementation of these developments is also indicated.

Despite over two decades of technology developments to date, there remains a substantial gap between the simulation of the air RF environment currently achievable with multi-£M threat simulators in ground-based T&E facilities and that experienced in real-world combat scenarios flown by military aircraft, for all but the simplest scenarios. There are also differences between ground-based facilities and between agencies using the same simulators (Stone, Bryson and Scarborough, 2009, pp.1-2).

The reasons for this on-going poor correlation between ground and flight test results are not yet fully understood. The EW T&E community, of which this author is a part, has, during the above period, sought to understand and resolve known shortfalls. Those efforts have already resulted in some considerable success, as witnessed by the extensive amount and types of testing now achievable in SIL/HITL/ISTF test facilities.

The Works describe the increased understanding of the military aircraft survivability topic and underpinning electromagnetics and EW topics achieved since the 1970's. The importance of RF threat simulators to ensuring EW receiver adequacy and fitness for operational use is now well understood, with a number of examples seen of the mission- and life-critical impact of not having such adequacy and fitness.

Enabling technology developments of RF threat simulators used for SIL, HTIL and anechoic ISTFs during the above period are now described in terms of key components and cardinal functions of a generic simulator as described in **Pywell** (2007). Whilst some can easily be placed in one of the system-level components of a simulator, this is not possible for many as their implementations straddle one or more boundaries between these components, as indicated in Figure 5-9.



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 5-9: Simulator schematic and key modelling elements

(from **Pywell**, 2007, with permission, Royal Aeronautical Society)

Key components in Figure 5-9 are consistent with the sub-systems for the US Navy-led, multi-service NEWEG system (United States. Department of Defence, 2011a; 2011c):

- Software System Control (SSC),
- Digital Generator (DGEN),
- Radio Frequency Generator (RFGEN), and
- Monitor And Analysis (MAA).

This indicates a consensus on the way ahead for enabling higher fidelity multi-emitter scenario T&E. It should be noted, however, that MAA also includes the RMS primary functions of emitter verification and ECM signal measurement and analysis. Although eminently sensible for a future (2015) threat simulator architecture, this is outside the scope of threat simulators discussed in this thesis.

Table 5-5 gives threat simulator technology status ca.1985 for those key component and cardinal functions. Table 5-6 shows main developments to date in those areas. The developments are believed to have been applicable, to a greater or lesser extent, to all of the many-channel threat simulator product types, *cf.* **Pywell** (2007, p.551). All have been applicable to the CEESIM type, with which this author has been most closely associated since the early 1990's.

An indication of this author's contribution is also provided in Table 5-6, using these codes:

A. Instigated and/or conducted research or other investigation, or provided technology leadership, on one or more technology development.

B. Directed and/or managed R&D or other investigations on one or more technology development.

C. Specified technology enhancement(s) for inclusion in a simulator acquisition.

D. Project and/or engineering managed acquisition and acceptance into T&E service of a simulator containing one or more technology development.

The level of contribution is attested to in the supporting letters at Appendix A from the (former) Typhoon DASS Product Manager and from Northrop Grumman Amherst Systems Inc., with whom this author has worked on RFEG and RMS technology developments over the last two decades.

The key components and cardinal functions are listed in columns one of Tables 5-5 and 5-6 are derived from **the Works**, in particular **Pywell** (2007) and **Pywell** and Midgley-Davies and **Pywell** (2010), and in the 2007-2012 technology development invited presentations identified in section 1.4. The first set of development requirements were initially identified in **Pywell** (1997).

Key Component and Cardinal Functions	Performance available ca.1985	Import
Threat and other emitter modelling		
Transmit antenna characteristics	Limited quality: limited data points/antenna; symmetrical (unrealistic), calculated models only; no scan modeling.	H
Pulsed and CW RF waveform generation	• Voltage Controlled Oscillator RF sources: Noisy; high spurii and harmonics; coarse frequency resolution; slow switching speeds limiting emitter multiplexing (MPPS per channel). • Limited intentional Modulation On Pulse (MOP) parameters – PW, PRI. • No pulse shaping (Un-intentional MOP) capability – needed for realistic emitter simulation.	H
Scenario capacity and capability		
Frequency range	Basic EW band, 2-18 GHz, in sub-bands.	H
Number of emitters in scenario	Up to 64: few 'foreground' emitters with full modelling of necessary RF characteristics, with remaining of lower quality 'background' emitters.	H
Number and motion of platforms	• Up to 256 platforms/scenario, straight and level flight. • 1-50 Hz platform geometry and position update rate.	H
Signal environment density and pulse drop-out	• ca. 1 MPPS maximum, using 5 RF sources, but limited scenario fidelity due to RF source limitations. • >5% drop-out, forcing a 'foreground'/'background' emitter operating philosophy.	H
Scenario repeatability	Poor repeatability.	H
Propagation and atmospheric effects modelling		
Scenario location and surface types	Flat earth modelling; no maps; no terrain; no surface roughness (land/sea).	H
Signal transmission effects: emitters-to-SUT antennas	Simple, radar range equation for atmospheric loss. No multipath; no ducting; no chaff modelling.	H
SUT receive antenna/aperture and receiver modelling		
SUT antenna interface and DF technique(s)	4, 6 or 8-port amplitude comparison.	H
Receive antenna and aperture modelling (laboratory mode)	Limited quality representations: • Data points/antenna and gain amplitude resolution (1 dB) • Highly symmetrical (but unrealistic) calculated models. • Relative polarisation between emitter and SUT antenna determined by simple look-up table.	H
Receiver modelling	No capability within simulator.	H
Operation and Maintenance		
Graphical User Interface and ease of use	Menu command input (user inputs number for required action). Limited 'help' functionality. 'Tear down' menus, sub-optimal ease of use compared to current day GUIs.	M
Calibration	Very slow (days), especially for multi-channel simulators, hampering availability for testing.	M
Diagnostics	Limited capability and number of error messages. Usually required external specialist equipment and expert staff to diagnose problems.	M
Availability	Limited - unreliable components and high calibration times.	H

Table 5-5: RF threat simulator technology developments – ca.1985

Key: Importance to improved scenario fidelity: H = High, M = Medium.

Key Function	Performance available now	Primary enablers of technology development	Author's contribution
Threat and other emitter modelling			
Transmit antenna characteristics	Much improved representations. 3D emitter models with thousand-fold increase in data points per antenna. Full modelling of scan patterns for most antenna types; limited for electronically-scanned arrays. User friendly antenna pattern visualisation and editing tools.	• Higher computing power and more memory • Improved real-time multi-processing • Faster digital circuits	A, B, C, D
Pulsed and CW RF waveform generation	Most RF source limitations resolved. High-speed Frequency-Locked Oscillators and synthesisers (high phase accuracy and coherency). Much improved pulse wave shape for FLO-based Amplitude MOP. High fidelity intra-pulse MOP, with (currently sub-optimal) high speed discretisation. Doppler modelling, simultaneous phase and amplitude outputs. Improved signal sources becoming available: Direct Digital Synthesis-based sources and Low Noise FLOs.	• Lower noise and cleaner RF sources • Faster, more capable and accurate digital circuits, especially pulse modulator components • Higher computing power	A, B, C, D
Scenario capacity and capability			
Frequency range	20-500 MHz; 0.5-2 GHz; 2-18 GHz (wideband); 18-40 GHz. Higher frequency extensions.	Wider band, lower noise and cleaner RF sources	B, C, D
Number of emitters in scenario	Up to 8192 complex emitters at digital level, with number at RF limited to 1024 simultaneously active by number/type of RF channels, channel pooling capability (pulses generated from multiple sources) and SUT-tolerable pulse drop-out.	• Improved real-time multi-processing • Higher computing power and more memory • Faster digital circuits	A, C, D
Number and motion of platforms	Up to 1024 fully maneuverable platforms/scenario. Full 6-DoF modelling and >1 kHz position and geometry update rates. Some can do real-time geometry update on pulse.	• Improved real-time multi-processing • Higher computing power and more memory	A, C, D
Signal environment density and pulse drop-out	Affordability-limited only by number of RF channels. Highest realistic scenario capability known is 5 MPPS. 2-3% (all emitters in scenario) pulse drop-out, which suffices for most T&E. Can programme 0-100% drop-out on a per-emitter basis, subject to number of RF channels.	• Lower noise and cleaner RF sources • Faster, more capable and accurate digital circuits, especially pulse modulator components • Higher computing power • Improved real-time multi-processing	A, B, C, D
Scenario repeatability	Excellent repeatability. User can introduce realism by programming different scan start positions and times.	• Higher computing power • Improved real-time multi-processing	C, D
Propagation and atmospheric effects modelling			
Scenario location and surface types	Full earth and mission-specific scenarios. Much improved capability available to user: Terrain roughness (vegetation) – multiple, user-defined patches within scenario; terrain screening (line-of-sight and scattering); and sea states.	• Improved real-time multi-processing • Higher computing power and more memory	A, C, D
Signal transmission effects: emitters-to-SUT antennas	Realistic modelling of atmospheric loss, radar horizon, rainfall and rates, ducting. Amplitude and polarisation changes caused by ground-bounce multipath and inter-platform reflections, including 3rd party tracking. Chaff modelling possible.	• Improved real-time multi-processing • Higher computing power and more memory	A, B, C, D
SUT receive antenna/aperture and receiver modelling			
SUT antenna interface and DF technique(s)	Interfacing and supporting modelling for various DF techniques, *e.g.* Multi-port amplitude comparison; Phase interferometer array(s); Time Difference of Arrival; Frequency Doppler.	• Faster digital and RF components • Higher resolution digitally controlled attenuators • Higher computing power and more memory	C, D
Receive antenna and aperture modelling (laboratory mode)	Much improved representations for SIL/HITL use. 6-fold increase in data points/antenna (calculated model). Better amplitude resolution (0.25 dB). Improved interpolation between User-inputted data points. Real-world measured models for installed antennas/apertures. Vector modelling for correct relative polarisation. User-friendly antenna pattern visualisation and editing tools.	• Higher resolution digitally controlled attenuators • Improved real-time multi-processing • Higher computing power and more memory	A, B, C, D
Receiver modelling	Amplitude and frequency modelling of SUT receiver threshold, and sector blanking, to prevent waste of RF channel capability generating signals at RF that the SUT cannot detect.	• Higher resolution digitally controlled attenuators • Improved real-time multi-processing	C, D
Operation and Maintenance			
Graphical User Interface and ease of use	• Windows-based, user friendly GUI on most. Some have 3D drag-and-drop capability. • Warning dialogs throughout to aid users. • Warnings and lock-outs to prevent disallowed parameter inputs, especially useful when building emitters and scenarios.	• Higher computing power and more memory • Advanced graphics cards • Widespread adoption of Windows GUI	C, D
Calibration	Much faster (including use of use of network analysers for up to an order improvement), batched and scheduled calibrations increase availability for testing.	• Higher computing power and more memory • High performance vector network analysers	C, D
Diagnostics	• Extensive Built-In Test capability - finds and reports >95% of faults without user intervention. • RF and digital tests at start-up and pre-/post-test enables quick isolation of failed/failing components.	• Higher computing power and more memory • Faster digital circuits	B, C, D
Availability	Significant improvement - for a large (11 channel) system a minimum of 500 hours mtbf is achievable (NEWEG 'Threshold' is >240 and 'Objective' is >720 hours).	• Improved RF and digital component reliability • Improved manufacturing processes	A, B, C, D

Table 5-6: RF threat simulator technology developments – Current situation and author's contributions

Most of the key components and cardinal functions identified in Tables 5-5 and 5-6 are relevant to most of the test mission types and sub-types in Table 5-1, although some are more important than others. For example, threat emitter transmit antenna pattern emulation is of less importance to the Mission Data Validation test mission, which focuses on the EW receiver's fast and accurate ID, than for specified performance verification mission where the SUT has to 'fly' though a multi-emitter scenario. All are relevant, to a greater or lesser extent, directly or indirectly, to achieving the Table 5-1 'mission rehearsal (emulation)' fidelity level of multi-emitter RF scenario test capability.

As discussed in section 5.3.2 it is currently not possible to accurately define where the optimum affordability boundary lies between further enhancing threat simulators for ground-based *vs*. flight testing on OARs (Anderson *et al.*, 2005; **Pywell**, 2007; **Pywell** and Midgley-Davies, 2010). Likewise it is not possible to:

- define the exact level of contribution of each development in Tables 5-5 and 5-6 to improved generation of multi-emitter scenarios at RF, although a relative indication is given in Table 5-5.
- Provide a Technology Readiness Level (TRL)[22] maturity profile for each development, given that they are simulator product-specific and thus mostly proprietary.

[22] TRLs and their applicability to EW D&D are explained in section 3.3.2 of **Pywell** (2010).

5.5 CONCLUDING REMARKS

This chapter has expanded on the development and utility of threat simulators for generating improved quality multi-emitter threat scenarios at RF for the T&E of EW receiver systems. It has described more than two and a half decades of technology developments that now enable more comprehensive evaluation of those systems than was previously possible, and has identified this author's technology leadership contribution to those developments.

These technology developments have led the EW T&E community to a position where substantially more RF EW receiver test missions can now be conducted adequately and with confidence in ground-based test facilities rather than by limited, expensive and difficult to repeat flight test on dedicated EW ranges.

From an EW T&E standpoint there are significant cost, time and risk reduction benefits to be had if sufficiently high correlation could be achieved between flight test results from EW ranges and results from ground-based facilities using RF threat simulators. Such a level of correlation would also be required to underpin satisfying a larger amount of V&V requirements *via* M&S, which would offer further cost, time and risk reduction benefits to platform programmes.

Unfortunately, despite the many technology developments to date, there remains a correlation gap. Whilst many of the possible causes are being investigated by various industry and military agencies in (at least) the USA and Europe, there is currently no guarantee that the desired appropriately high correlation can ever be achieved. A number of potential further technology developments have been identified (**Pywell** and Midgley-Davies, 2010) and a major pan-service US project, NEWEG, is thought likely – subject to continued funding approval - to resolve many of the outstanding issues by end-2015 (United States. Department of Defence, 2011a; 2011c; Haystead, 2013).

Whilst the above considers the technical aspects of achieving 'mission rehearsal (emulation)' quality fidelity of multi-emitter scenarios at RF, affordability is now of equal if not greater importance to world-wide defence budgets. The development of a method for affordability-driven simulator enhancement priority assessment, described in this chapter, has enabled robust Value for Money assessment of 29 potential threat simulator enhancements identified by Pywell and his colleague, Midgley-Davies.

Chapter 6

CONCLUSION

6 CONCLUSION

6.1 CONCLUSION

The aims have been met, in that this thesis encapsulates over three decades of this author's critical investigation and evaluation of a number of subordinate elements of air platform survivability. This thesis has, in particular, focused on RF EW receiver systems in multi-threat environments, with emphasis on high-fidelity test technology development of high-value and complex RF threat simulators that are used to comprehensively evaluate those systems. This thesis provides a critical appraisal of **the Works**, which evidences the encapsulation, and this author's related activities. This appraisal demonstrates the research progression in the selected technological domain and that **the Works** make a significant and coherent contribution to knowledge.

Conclusion elements drawn from the body of the thesis are:

- Survivability is essential for military platforms. EW is one of its many sub-components that have to be balanced to provide effective and affordable force projection in support of national policy. RF EW receivers are a key element of a platform's DAS and are crucial to survivability during combat. Without fully adequate, correctly programmed receivers, the risk of mission, aircraft and aircrew loss to threat weapon systems is high. Exhaustive T&E is required with high-fidelity, multi-emitter simulated RF threat scenarios to assure this adequacy and programming correctness prior to combat.
- Significant limitations existed in the 1970's on the generation of high-fidelity, multi-emitter scenarios at RF. Many have now been resolved, although remaining fidelity issues still lead to poor flight-to-ground test correlation for multi-emitter dynamic scenarios. To close this gap, potential technology enhancements were identified by this author and his colleague Midgley-Davies, who together also developed a robust technology prioritisation assessment method that addresses today's need for increased VfM.
- The technology development route driven by this author since the 1970's is in line with the multi-$M, 2011-initiated US NEWEG project, the Next-generation EW Environment Generator. The combination of further research directions identified by this author (section 6.3) and the NEWEG

project's 'Threshold' and 'Objective' Key Specification Attributes offer the promise of resolving many outstanding fidelity elements.

A central thread of the thesis concerns this author's long-stated postulation that it might one day be possible to confirm almost all aspects of EW RF receiver performance by testing on ground-based facilities, enabled by enhanced RF threat simulators, rather than by expensive and difficult to repeat flight trials.

- This is extremely important to defence customers and industry alike in these austere times, as this will enable cheaper, shorter and less risky platform EW development and upgrade programmes. As importantly, this will also enable the earliest possible detection of EW receiver problems, whose cost-to-fix – in common with those of most avionic systems - goes up significantly the later they are discovered in a programme (Slater and Pywell, 2012).
- **The Works** and this thesis identify two and a half decades of simulator technology developments, potential technology enhancements and further research directions (section 6.3) that, when taken as a whole, suggest the postulation may be proven within the next decade, if not earlier.
    - Many prior fidelity limitations on multi-emitter scenario generation have been resolved and the remainder are steadily being overcome. Evidence is presented that this author has provided substantial technology leadership and direction to the EW community in the area of RF threat simulator developments towards this goal.
    - Only a small residual element of EW receiver performance would remain to be verified by flight test - those aspects that can only be flight-proven. Residual testing can be more focused, with higher success probability, as most test points will be confirmatory rather than experimental.
    - It will be possible to conduct some operational evaluation (performance validation) *via* ground test rather than traditional flight test, although there will always be a need for flight test of entire EW systems, especially for tactics development and training in support of operations and exercises.

The optimal mix of EW T&E capabilities and techniques described in this thesis, primarily enabled by developments in high-fidelity, multi-emitter RF threat simulator technology, will lead to more cost-effective EW T&E and will support optimised platform survivability and increased mission success probability.

6.2 CONTRIBUTION TO KNOWLEDGE

The Works, when taken as a whole, represent a significant contribution to the body of aerospace knowledge across the domains of Survivability, EW systems, EW T&E and RF threat simulation.

The main claim to originality of **the Works** is in their development of public release reference material in the sensitive topic area of EW and EW T&E for the education of novices of graduate level and upwards, for the advisement of technical professionals, experienced testers and academics, and for the guidance of programme managers. In particular, the invited chapter on EW design and development in the nine-volume Encyclopedia of Aerospace Engineering (**Pywell**, 2010), and the substantially updated NATO EW T&E handbook (Welch and **Pywell**, 2012) are international reference works with wide applicability and longevity, enabling world-wide dissemination of the contribution to knowledge.

Particular **Works** have more specific claims to originality:

- The 2007 '*Developments in RF simulator technology – approaching the affordable fidelity limit'* publication (**Pywell**, 2007), for which this author received a Silver Award from the UK's Royal Aeronautical Society, is the only known comprehensive discourse on RF threat simulator technology capabilities and limitations, developments and potential future enhancements. Its examination of the driving factors that determine how close to emulation of multi-emitter RF scenarios is likely to be affordably feasible has focussed simulator supplier product development, as witnessed by simulation fidelity enhancements now available and as attested in Appendix A.
- The 1999 '*The new enigma: Increased survivability with reduced cost?*' publication (**Pywell** *et al*., 1999) was, in effect, a UK position paper on the topic and resulted in part from this author's participation in a major NATO Research and Technology study on '*Requirements and Options for Future NATO Electronic Warfare Capabilities*'. At the time it was the only work found in the literature that addressed the complex inter-relationship between survivability and its components - Damage Avoidance (including EW), Damage Tolerance and Damage Repair - and affordability.

- The 2010 '*Improved test capabilities for cost-effective performance evaluation of airborne electronic warfare systems'* publication (**Pywell** and Midgley-Davies, 2010) identified, for the first time, key areas where the EW T&E community could enable or contribute to resolution of a number of significant 21st century aerospace challenges. In particular it identified underpinning research and other investigations required to enable realisation of cost, time and risk benefits. It also focused on RF threat simulation developments necessary to enable more performance verification evidence to be gathered via ground testing in the laboratory and in anechoic chambers rather than by expensive and difficult to repeat flight testing on limited capability open air ranges.

In terms of the coherent theme examined in this thesis, that of multi-emitter RF scenario generation with high enough fidelity for adequate verification of EW receiver performance, thereby increasing platform and aircrew survival probability under combat conditions, **the Works** substantially add to the publicly available literature base. They also contextualise the importance of RF threat simulation to the world-wide defence and military communities.

The investigations of RF threat simulation fidelity limitations and identification of enhancements are seldom seen either in conference presentations or, even less so, in the literature. This author's representation of the UK and his company on various EW-related NATO R&T and Industrial Advisory Group studies has reinforced the findings of **the Works**.

6.3 FUTURE RESEARCH DIRECTIONS

Suggested future research directions follow, with an initial view of importance ranking. All offer worthwhile simulation fidelity improvements for multi-emitter scenario simulation at RF, with the aim of enabling maximum correlation between ground and flight test results on RF EW receivers. All support the target of conducting most EW RF receiver T&E on ground-based facilities and many would lead to improved Mission Data Validation quality and enhanced problem evaluation capability. Most were initially identified in the more recent **Works**, in particular **Pywell** and Midgley-Davies, 2010.

The suggested research directions specifically concern a single threat simulator used to test a single manned or unmanned platform's EW receiver(s). Whilst this thesis does not explicitly cover the use of multiple threat simulators to stimulate multiple, data-linked platforms' EW receivers, these research directions are considered equally relevant to those cases.

1. **Real world transmit antenna pattern modelling:**
   Research is required to underpin improved modelling of transmit antenna patterns of threat and other emitters. Initial investigations strongly suggest this is a major source of SUT-received RF environment error compared to the real world, especially for multi-emitter dynamic scenarios. Real world patterns tend to be irregular, unlike the highly symmetrical 'calculated' models often used in the COTS type threat simulators used in laboratories and anechoic chamber ISTFs. Transmit antennas also exhibit non-linearities, including radiation spill-over, random polarisation in side-lobes, and ground-bounce (multipath) in close vicinity to the antenna. As EW receiver detection sensitivities improve, especially *via* 'digital receiver' technology and their powerful processing algorithms, this improved modelling will become more important as those receivers will be more sensitive to these effects.
2. **Correlation of threat simulator outputs to those of real-world emitters**:
   Research is required to enable RF threat simulators produce better representations of threats and other radar emitters. This should build on the work of Anderson *et al.* (2005), who identified real radar waveform features that are not usually replicated by threat simulators used in the laboratory and anechoic chamber. These features included mode switching transients, additional intra-pulse modulations, and other anomalous behaviours.

The intra-pulse sample period necessary to accurately mimic real radar waveforms, including pulse ringing, droop and rise/fall times, should be investigated. Alternate technology implementations to achieve the above should also be investigated as, currently, the high speed synthesiser-based high-fidelity intra-pulse modulation capabilities currently used for this type of work are expensive and have limited capability in this area.

3. **Modelling of intra-platform effects**:
   Improved modelling of own platform effects are required for laboratory testing if mission rehearsal quality test capability is to be achieved. This will require a better understanding of platform-specific reflections and electromagnetic energy scattering around the platform prior to that energy entering antenna apertures, better modelling of obscuration by own platform features and determination of incident pulse shape degradation effects. This is in addition to the reasonably well understood computational electromagnetic modelling of antennas installed in the local airframe. The required real-time modelling of these intra-platform effects is unlikely to be achievable in the near future, so alternate modelling strategies should also be researched.
4. **Further development of technology upgrade prioritisation tool**:
   Further development of the technology prioritisation assessment method described in this thesis would enable a more robust ranking of disparate potential upgrades. Underpinning investigation is required in two areas:
   - Exploration of reasons behind the apparently low range of scores determined by Pywell and Midgley-Davies, compared with the theoretical maximum, and method optimisation.
   - Expansion of the bubble diagram assessment tool to include the effects of acquisition and through-life support and maintenance costs. Development of a three-dimensional bubble diagram to enable visualisation of both this whole life cost impact and effects of upgrades 'batching' to achieve lower net cost per upgrade candidate.

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Appendices

A. Supporting letters and awards

B. Definition of test and evaluation

APPENDIX A:

SUPPORTING LETTERS AND AWARDS

September 2012

<u>Supporting letter for Mike Pywell</u>,

Mike has been involved in the Test and Evaluation (T&E) of Electronic Warfare (EW) and Defensive Aids Sub-Systems (DASS) since the early 1980's. He has extensive experience across the aircraft survivability, EW, DASS and T&E domains, and has participated in many NATO Research and Technology and Industrial Advisory Group EW studies for the UK and the company.

His particular area of expertise is in the T&E of RF EW receiver systems and he is an internationally recognised expert on the high value RF threat simulators used to test these systems in the laboratory and anechoic chamber facility environments.

Mike has been involved in BAE SYSTEMS' EW Test Facility, with its aircraft-sized anechoic chamber, since the outset. He conducted the 1985 initial feasibility study and led the team that specified the requirements for the facility. In particular, he developed and was the lead co-author of the 1991-2 specifications for the two threat simulators subsequently used for the development of the Eurofighter Typhoon aircraft's DASS. He led the 1996-7 specification for three threat simulators for the development of the Nimrod MRA4 aircraft and led the 2001-5 specification of two threat simulators for the RAF's in-service support of the Typhoon and Nimrod MRA4 aircraft. He was also responsible for the 2006-12 'refresh' of the DASS test instrumentation for the EWTF, comprising (primarily) two new RF threat simulators and a response measurement system for RF Electronic Countermeasures (ECM) testing. He was also responsible for acquisition of a sister set of similar test equipment for another project and another threat simulator for a third project. In each case he led the development of the specifications for the five threat simulators acquired.

Throughout the above period Mike has investigated required capabilities and technical-cost trade-offs, and has researched potential solutions to limitations affecting adequate simulation of single-emitter simulations and multi-emitter RF threat scenarios. In this regard he has developed a very special relationship with the major supplier (Northrop Grumman Amherst Systems Inc.) which has paid dividends to the Typhoon project overall. He is widely published on the topics of survivability, EW, and RF threat simulation, has given Amherst-invited presentations on potential technology developments for threat simulators and ECM response measurement systems, and has provided lectures to the IET and AOC.

Throughout my years as Typhoon DASS Product Manager, Mike has provided a great deal of advice and consultancy to the Typhoon project team e.g. EW T&E enhancements, potential future upgrades to EWTF and test equipment, test philosophy ideas for Typhoon DASS upgrades. Mike receives a great deal of respect from the DASS team, his commitment to continuous improvement and suggestions for future capability enhancements and his depth of specialist technical knowledge are very much acknowledged.

Yours sincerely,

M. Monk CEng FIET
Typhoon DASS Product Manager (2007-12)

BAE Systems 14 December 2009
Mr. Nick Bell Capability Manager
W423A (EW Test facility)
Warton Aerodrome
Lancashire
PR4 1AX
United Kingdom

BAE Systems
Mr. C. Lane Operations Manager
W423A (EW Test facility)
Warton Aerodrome
Lancashire
PR4 1AX
United Kingdom

Subject: Letter of Appreciation for Mike Pywell, BAE Systems – UK

Dear Sirs,
I would like to take this opportunity to express my appreciation for the support and excellent work, which Mike Pywell contributed to the NATO RTO study SAS-064.

The study was initiated on request of the Air Forces Advisory Group (NAFAG) subsection Air Capability Group 3 (ACG) as successor to the SAS-011 study. It was of great benefit to the task group that Mike Pywell, who already participated in SAS-011, did explain ideas and intentions behind the derived results of this study. It was his achievement that the task group was well aware of achievements and results of SAS-011, which was the basis of the study group's work. He than undertook the cumbersome task of determining which of the recommendations had been implemented and which were still pending. This work was one of the cornerstones to the study as it enabled the task group to assess developments and changes with respect to capability gaps. The additional ideas presented by him regarding content and layout were a significant contribution to the study outcome.

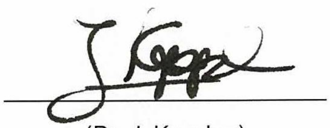
As during previous studies Mike Pywell was the only UK industrial member of the team and one of three UK delegates, the others being Mr. Martin Ruskell and Mr. Liivet both from NATO JEWCS. Although all three UK delegates contributed significantly to the international team, I want to highlight Mr Pywell's outstanding contributions.

The study benefitted from Mike Pywells broad experience and his professional background in the field of Electronic Warfare. He provided valuable inputs to assess the complex field of Directed Energy Weapons and future roles of UAV's in Electronic Attack comprising SEAD and DEAD missions.

In addition his experience did encourage the task group to an early start with the final report, which than allowed for a timely finish. His involvement in the editorial team was essential to the quality of the final report.

It has certainly been a pleasure working with Mike Pywell over the last couple years and I greatly appreciate his professionalism and enthusiasm for the EW mission. Getting to work with people like Mike Pywell is one of the highlights of being in a collaborative NATO study like ours has been. Mike has certainly represented your company and your nation well, and I thank you.

Best Regards,



(Dr. J. Keppler)

Chairman SAS-064
IABG

Voice: [+49] 89 6088-2773
Mobile: [+49] 1714233003

Email postscript:
If you would like a signed paper copy of this letter please reply by email and I can transmit via post at your request. Also, please forward this letter to anyone in your company that you feel would be appropriate.

Northrop Grumman Systems Corporation
Amherst Systems, Inc.
1740 Wehrle Drive
Buffalo, New York 14221-7032

21 March 2013

To Whom It May Concern:

It is my pleasure to provide this recommendation, and to highlight the significant contributions Mike Pywell has made not only to our organization, but to the Electronic Warfare (EW) industry as a whole.

Mike first started working with Amherst Systems, Inc. in 1991, and over the intervening years he has been involved in requirements capture, specification, acquisition and operation of a number of our Combat Electromagnetic Environment Simulator (CEESIM) RF threat simulator and Signal Measurement System (SMS) ECM Response Measurement System products.

He is very well respected by our CEESIM and SMS technical experts and our project managers, and is known to be likewise well respected by other international users of this complex and high value EW test equipment. Some of his EW-related publications, especially the 2007 one 'Developments in RF Threat Simulator Technology – Approaching the Affordable Fidelity Limit' and the 2012 NATO EW Test and Evaluation handbook, are a testament to his knowledge in the threat simulation technology area and the wider domains of EW and aircraft survivability.

Mike has been particularly active in the Research and Development of multi-emitter RF threat scenarios, being instrumental in identifying, stimulating and guiding our research and other technology performance enhancement efforts for over two decades. In 2001-3 he also managed two BAE SYSTEMS-funded R&D contracts in which Amherst Systems investigated, under his direction, a number of technology and operational topics, including scenario modelling performance, antenna pattern modelling, RF pulse shaping, improved noise performance, and reliability and calibration enhancements.

In more recent years he has helped us focus on affordability aspects and what threat simulator enhancements would be required to optimize the amount of EW test work that could be done in the laboratory and in aircraft-sized anechoic chambers, compared to expensive and difficult to repeat flight test. The CEESIM and SMS technology enhancements vs. affordability trade-offs he and his colleague M. Midgley-Davies investigated in 2009-10 was particularly interesting and has informed our internal development efforts.

He continues to drive us towards the 'emulation' scenario fidelity goal that could, theoretically, enable ***all*** EW receiver testing to be done via ground-based testing only – with significant cost, timescale and risk benefits potential for defense ministry customers and industry alike.

He has also, at our invitation, provided excellent, stimulating and thought-provoking presentations to the UK CEESIM User Conferences/Review Meetings in 2007, 2009, 2011 and 2012. The last, where he and our Director of Business Development co-led a discussion session focusing on whole life affordability opportunities and risks, was particularly well received by the UK User community, represented by MoD and Industry attendees.

The relationship Amherst Systems has with Mike Pywell, and his willingness to share significant knowledge and expertise, is greatly appreciated and undoubtedly enhances our ability to remain on the cutting edge of technology. His dedication is truly an asset to the EW community and is positively reflected by his continued success.

Sincerely,

AMHERST SYSTEMS, INC.

Joseph C. Downie
Site Director

UNITED KINGDOM CHAPTER
Association of Old Crows

Bank End
1, Fernden Rise
Godalming
Surrey
GU7 2BF
07789993162

Mr Ian MacDiarmid
Head of Electromagnetics
W391
BAE SYSTEMS
Warton
Preston, Lancashire
PR4 1AX

29 May 2012

Dear Ian,

I would very much like to thank you and BAE SYSTEMS for providing in Mitch Midgley-Davis an excellent speaker for our recent UK Chapter meeting at the RAF Club in London. The presentation was the best technical paper we have received for several years. It started by providing an exceptionally good introduction, which immediately focused the audience's mind on what is now a significantly complex, time consuming and potentially very expensive challenge, to properly validate and qualify modern integrated EW systems, at weapons systems level. The presentation went on to describe, at just the right level of technical detail, the major investment by BAE SYSTEMS, in the unique electromagnetics facility and the related cost-effective procedures currently in use at Warton. The briefing stimulated a large number of very interesting questions, which Mitch handled in an exceptionally professional manner.

As Mitch indicated during the presentation, the paper he delivered was jointly prepared by himself and Mike Pywell - EW Technologist & Project Manager – Typhoon EW Rig Support Equipment. Both of them should be congratulated on their individual, unique and very significant contributions to EW systems evaluation. One of the major aims of the AOC UK Chapter is to promote a wider understanding of all matters relating to EW. The paper by Mitch and Mike is a significant contribution to our aim. I think it would be in all our interests and those of the UK, to see the paper presented more widely to UK and international audiences. If you agree, we can discuss further and perhaps I can advise you on how this paper could be introduced to a wider audience of EW specialists and industry leaders. If you know of other equally good EW related papers, we would be pleased to receive them and perhaps make a paper by BAE SYSTEMS an annual event in the AOC UK Chapter's calendar. The UK Chapter Board is keen to expand the awards we make, which are currently focused on the military and academia, to include excellence in UK industry. It goes without saying that both Mitch & Mike would be particularly appropriate candidates for an "AOC UK Chapter EW Technology Achievement Award", if one had existed!" The challenge will be to find a way to enthuse members in industry to nominate suitable candidates, either for UK or international AOC awards.

Finally, please pass on my personal thanks and those of the Board and Members of the Chapter to Mitch and Mike for their excellent work which shows BAE SYSTEMS in the best possible light.

Yours John

John Clifford OBE
President UK Chapter

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 412TH TEST WING (AFMC)
EDWARDS AIR FORCE BASE, CALIFORNIA

412 TW/CT
195 East Popson Avenue
Edwards Air Force Base, California 93524-6843

BAE Systems
ATTN: Ms. Joanne Latham
W423A (EW Test Facility)
Warton Aerodrome
Lancashire
PR4 1AX
United Kingdom

Dear Ms. Latham

As NATO RTO SCI-203 Champion, I wish to express my sincere appreciation for the outstanding work Mr. Mike Pywell did to produce the updated AGARDograph Handbook that is regarded as the current standard of excellence by our NATO Flight Test Technology Team (FT3). It was obvious to me that Mike's decades of experience in Electronic Warfare Test and Evaluation (EW T&E) were key to writing a document with a solid and broad technical foundation that could be understood by both experts and novices. This timely update to a widely used flight and ground test handbook will ensure we have an up to date and technically relevant handbook on the subject.

Mike's broad knowledge and extensive experience were invaluable to the SCI-203 EW T&E handbook effort. The AGARDograph update produced a comprehensive handbook that introduces novice EW testers to a disciplined test approach while providing a concise reference for more experienced testers and program managers. Mike extensively revised, amended, and edited the two chapters addressing EW T&E Resources and Facilities and Modeling and Simulation for EW T&E. Mike's has a wealth of knowledge on these topics and, when necessary, had the contacts to tap other experts to provide specialized content. These chapter updates addressed advances in the EW T&E field since the previous edition was published while greatly expanding the handbook content.

A key feature of the handbook is an extensive listing of test facilities and resources available to NATO and Partnership for Peace countries. The EW T&E Facility Descriptions Annex identifies 21 facilities, provides a brief description of each test capability, and provides points of contact. Mike's extensive professional contacts and knowledge of European test facilities and resources ensured that they were well represented. Mike also provided great support to all other areas of the handbook. Mike is a superb technical writer who provided outstanding editorial guidance to his co-author. His attention to detail helped ensure that the document was consistent and complete from start to finish.

It has certainly been a pleasure to have Mike on this project for the last couple of years; he has had a lasting impact that will benefit all NATO allies for years to come. I appreciate your willingness to allow Mike to be part of our team.

Sincerely

O. Carter Wilkinson

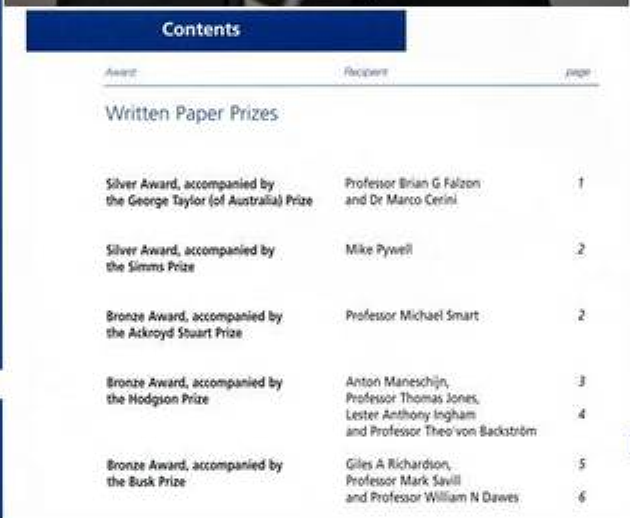
O. CARTER WILKINSON
Technical Director, 412th Test Wing

Mike receiving the award at the Society in London from the President, Capt. David Rowland


ROYAL AERONAUTICAL SOCIETY

Medals and Awards

The Presentation of the 2007 Written Paper Prizes 10 July 2008


Contents

Award	Recipient	page
Written Paper Prizes		
Silver Award, accompanied by the George Taylor (of Australia) Prize	Professor Brian G Falzon and Dr Marco Cerini	1
Silver Award, accompanied by the Simms Prize	Mike Pywell	2
Bronze Award, accompanied by the Ackroyd Stuart Prize	Professor Michael Smart	2
Bronze Award, accompanied by the Hodgson Prize	Anton Maneschijn, Professor Thomas Jones, Lester Anthony Ingham and Professor Theo von Backström	3 4
Bronze Award, accompanied by the Busk Prize	Giles A Richardson, Professor Mark Savill and Professor William N Dawes	5 6


ROYAL AERONAUTICAL SOCIETY

THIS IS TO CERTIFY THAT THE

SIMMS PRIZE 2007

FOR THE BEST PAPER ON ELECTRICAL, ELECTRONIC AND OTHER SYSTEMS (INCLUDING THE GROUND ENVIRONMENT)

IS AWARDED TO

MIKE PYWELL

FOR HIS PAPER "DEVELOPMENTS IN RF SIMULATOR TECHNOLOGY – APPROACHING THE AFFORDABLE LIMIT"

THIS TENTH DAY OF JULY 2008

PRESIDENT

CHIEF EXECUTIVE

Foreword

For both of us, and on behalf of our respective institutions, it is a privilege and a pleasure to have been asked to introduce the *Encyclopedia of Aerospace Engineering*.

In a very real sense, this Encyclopedia represents the best aspirations of the Royal Aeronautical Society and the American Institute of Aeronautics and Astronautics. Both of our organizations seek to advance the body of aerospace knowledge, and both understand that the aerospace field is dynamic, multidisciplinary, and multinational in character.

The Encyclopedia is a unique vehicle that offers a snapshot of this globally-shared body of knowledge, a shared sense of global enterprise, shared technical perspectives and challenges, a shared sense of pace, innovations and new horizons and in particular a shared focus on the importance of education and training – all with respect to an industry and a set of disciplines that have moulded and continue to shape the world in which we live.

This shared body of knowledge transcends the national, commercial, organizational and technical disciplinary boundaries within which we conduct our day-to-day business, albeit that the latter are an essential spur to often competitive but almost always innovative and constructive endeavour. It is therefore particularly and incredibly exciting to see the launch of a thoroughly professional attempt to consolidate and make available the essence of that body of knowledge in encyclopedic form.

It is difficult to overstate the impact that the aerospace field has had on our world. The early visionaries of aerodynamics, from Sir George Cayley to the Wright Brothers, could hardly have imagined how thoroughly aviation, let alone spaceflight, have changed our civilization – making our planet a much smaller place, allowing for instantaneous communication anywhere on the globe, providing for the large-scale transport of people and supplies, and offering a glimpse of our planet and ourselves from the unique perspective of outer space. Aerospace engineers have not only contributed directly to our collective body of knowledge, but they have driven advances in a wide range of related fields, from basic mathematics, electronics and materials science, to biology and human factors. It is therefore especially appropriate that we capture the essence of the field in these volumes at this point in time.

At first sight it is not readily apparent that it would be possible to distil even the key elements, let alone the details, of a hugely diverse range of aerospace engineering technologies and areas of study into a single coherent framework. And yet, this ambitious work has attempted to do just that, and more. In that sense the Encyclopedia is nothing if not a bold, visionary, even courageous concept.

The result has drawn on the expertise of the very best and brightest currently in our field. It is, we think, a tribute to the originators and authors, who are to be congratulated on an outstanding contribution to the aerospace profession.

At a practical level the Encyclopedia is designed to be eminently readable and accessible, albeit targeted at a particular level of understanding. We expect to see it widely utilized as an authoritative work of reference, as a key tool for learning and professional development, and possibly as a benchmark for coursework and technical module design and accreditation recognisable across national and organizational boundaries.

The work represents a milestone and marker in the continuing development of aerospace engineering and science at the beginning of the second century of manned, powered flight and as the promise of space seems increasingly resurgent.

We are proud, jointly, to commend it to you.

Dr. Mark J. Lewis
President, American Institute of Aeronautics and Astronautics and Willis Young Prof. and Chair of Aerospace Engineering, University of Maryland, College Park, MD, USA
and
Dr. Mike Steeden
President, Royal Aeronautical Society, 2009-10, UK

APPENDIX B:

DEFINITION OF TEST AND EVALUATION

A MODEL TO DESCRIBE THE FUNCTIONS AND ROLES OF TEST AND EVALUATION (T&E) IN THE LIFE CYCLE PROCESS

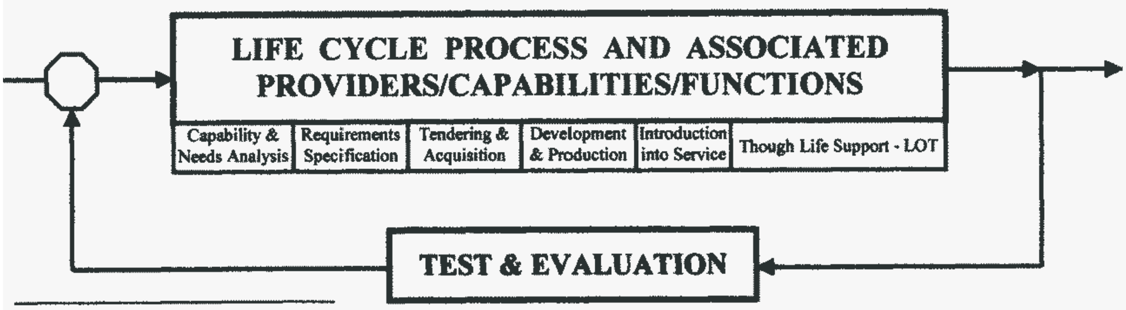
What is T&E ? - a Simple Definition of this Engineering Discipline

Test and Evaluation (T&E) is the "*feedback loop*" of the Systems Engineering *Life Cycle Process*, which is applicable to all stages of the process, and embodies the following functions and roles :

- T&E oversights and provides the proof that a *product* or a *system* complies with and conforms to the specification and, moreover, meets the *needs* of the end user.
- T&E is a "*Womb to Tomb*" philosophy and an important *technology enabler.*
- T&E is a means of "*maximising return on expenditure*" (according to a former President of ITEA[2], ADM Pete Adolph (USN), "*T&E is about getting the best bang for your bucks!*").
- T&E is an integral part of the process for achieving "*cost effectiveness*" and "*value for money*".
- T&E rigour and processes provide the *objective data* needed to achieve *compliance, conformity, probity, accountability, transparentness and fair dealings* in contracting activities.
- T&E assists the customer to be a "*smart buyer*" and obtain "*value in technology*".
- T&E is a broad set of activities and functions, including the following :
  - Systems Testing eg. Flight Test (Developmental, Certification, Acceptance, Production)
  - Certification, Classification and other Regulatory Activities/Functions
  - Developmental Test and Evaluation (DT&E)
  - Acceptance Test and Evaluation (AT&E)
  - Operational Test and Evaluation (OT&E)
  - Independent Verification and Validation (IV&V)
  - Risk Analysis & Risk Assessment & Risk Planning (eg. System Safety Analysis)

"*To be effective, T&E should be independent of ... but integrated with the Life Cycle Process and the associated providers and their capabilities.*"

A Simple Model to Describe T&E ...."*the feedback loop for all stages of the Life Cycle Process*"



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(2) ITEA - International Test and Evaluation Association