Developments in RF simulator technology – approaching the affordable fidelity limit

M. Pywell
BAE Systems – Military Air Solutions
Warton, Lancashire
UK

ABSTRACT

Technology developments in radar frequency simulators of the type used to verify the performance of complex electronic warfare systems are described. The successful verification of this performance prior to combat use is a necessary pre-requisite of military platform survivability and mission success. These simulators and associated modelling and analysis tools have enabled a major shift during the last 15 years from expensive and limited flight trials to repeatable laboratory and anechoic chamber tests, although they will never totally supplant those trials. Most limitations of the early days of many-channel simulators, 25 years ago, have been resolved or adequately and – as importantly – affordably mitigated, largely enabled by computing power increases. Limitations remain that will, within affordability constraints driven by Defence Ministries worldwide, prevent perfect simulation ('emulation') and the attendant, tantalising but utopian goal of laboratory and chamber test results that *precisely* match those from flight test and combat.

NOMENCLATURE

AMES	Advanced Multiple Emitter Simulator
AMOP	amplitude modulation on pulse
BAF	Benefield Anechoic Facility
AOA	angle of arrival
CEESIM	Combat Electromagnetic Environment Simulator
CHAFF	chopped aluminium Foil
CP	circularly polarised
CW	continuous wave
DF	direction finding
DTO	digitally-tuned oscillator
ECM	[RF] electronic countermeasures (jammers)
ELINT	electronic intelligence
EOB	electronic order of battle
ESM	electronic support measures
EW	electronic warfare
EWsT	EW Simulation Technology Ltd.
FLO	frequency-locked oscillator
FMOP	frequency modulation on pulse ('chirp')
HFIM	high-fidelity intra-pulse modulation
HSS	high-speed synthesiser
ID	identification
LCC	life cycle cost
LPI/LPD	low probability of intercept, detection
MPPS	mega-pulses per second
OAR	open air range
PD	pulse doppler
PMOP	phase modulation on pulse
PRI	pulse repetition interval
PW	pulse width
RF	radio/radar frequency

Paper No. 3191. Manuscript received 8 March 2007, revised version received 6 August 2007, accepted 20 August 2007.

https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press

RSS Radar Signal Simulator
RWR radar warning receiver
Rx receive(*r*)
SEI specific emitter identification
SNR signal-to-noise ratio
STS slow-tune synthesiser
SUT system under test
T&E test and evaluation
TDOA time difference of arrival
VCO voltage-controlled oscillator
UMOP unintentional modulation on pulse
VV&A verification, validation and accreditation

1.0 INTRODUCTION

This paper considers technology developments in radio/radar frequency (RF) threat simulators, hereafter referred to as 'simulators', as used for the test and evaluation (T&E) of electronic warfare (EW) receiver and processing systems. It focuses on commercially available large simulators operating in the modern-day most important radar band (0·5-40GHz), as used in EW laboratories and anechoic chamber facilities world-wide. It draws on BAE Systems' considerable experience in this area with two of the world's major simulator types – CEESIM and AMES†. These simulators comprise the computing, digital and RF components necessary to generate RF signals for injection into, or radiation at, EW receiver systems. Figure 1 shows the range of such simulators.

T&E in this context comprises activities conducted in support of the design, development and in-service support of EW receiver systems on air, sea and land platforms. Such systems, see Fig. 2, comprise radar warning receivers (RWRs), electronic support measures (ESM), electronic intelligence (ELINT) systems and electronic countermeasure (ECM) receivers – generically known as systems under test (SUTs). RWR/ESM are fitted to most military aircraft that have to go in harm's way, with ECM also fitted to higher value assets and those who cannot avoid engagement by deadly threats. RWR/ESM/ELINT cardinal capabilities of direction finding (DF), emitter/platform identification (ID) and emitter location are covered elsewhere, e.g. Ref.1.

† Advanced Multiple Emitter Simulation (AMES) simulators, originally produced by Advanced Systems Development Inc. (New York, USA), are now produced by Northrop Grumman, Amherst Systems Inc., Buffalo, USA. Combat Electromagnetic Environment Simulation (CEESIM) simulators have always been produced by the same Amherst Systems Inc.



Figure 1. Typical CEESIM threat simulators.
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	RWR*	ESM*	ELINT
PURPOSE / **RECEIVER COMPONENT**	WARN AIRCREW OF RF-GUIDED THREATS & CUE COUNTERMEASURES	DETECT/IDENTIFY & PRECISELY LOCATE RF-GUIDED THREATS AT LONG RANGE. ECM CUEING.	INTERCEPTION & ANALYSIS OF HOSTILE NON-COMMUNICATIONS EMITTERS. DETERMINE ENEMY EOB. NO ECM CUEING.
ANTENNAS (FREQUENCY SUB-BANDED)	4 SPIRALS/FREQUENCY BAND FOR AZIMUTH. 4 MORE FOR ELEVATION	INCREASED No./TYPES OF ANTENNAS, INCLUDING PHASED ARRAYS, SPINNERS	USUALLY MULTIPLE, FREQUENCY-BANDED OMNI AND DF ANTENNAS
RECEIVERS, ANALYSIS & PROCESSING	WIDEBAND & SUB-BANDED, CHANNELISED RECEIVERS. ANALYSIS SHARED WITH STAND-ALONE PROCESSOR	AS RWR + OTHER TYPES, e.g. IFM. BETTER DF TECHNIQUES. INTEGRATED PROCESSING	MULTIPLE FREQUENCY SUB-BANDED SEARCH/ACQUISITION & SET-ON/ANALYSIS RECEIVERS. INTEGRATED PROCESSING NOW COMMON
RECORDING	RARE	BECOMING COMMON	DATA ALWAYS RECORDED
DISPLAYS & CONTROLS	OFTEN STAND-ALONE	OFTEN PART OF INTEGRATED AIRCRAFT D&C	PER-RECEIVER D&C COMMON. LATEST HAVE INTEGRATED D&C

*ECM RECEIVERS HAVE RWR/ESM CAPABILITY

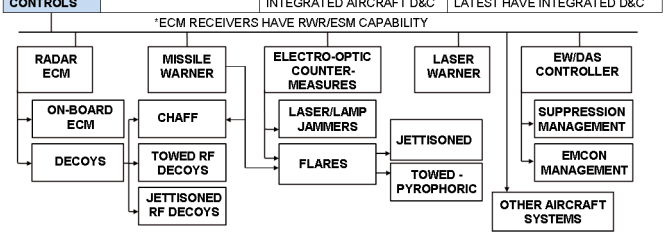


Figure 2. Receiver systems in airborne EW suite.

These simulators, which usually involve multi-$M capital expenditure, are essential for SUT development and support. In turn, these SUTs are crucial to assuring platform survivability and thus mission success. As the international community strives to achieve optimum survivability through platform-specific balancing of stealth (radar, infra-red and other signatures), EW systems, electromagnetic hardness and intrinsic aircraft vulnerability,[2,3,4,5] the importance of simulators has grown.

Key requirements for RF simulators and their use in the EW T&E process are stated. Simulator suppliers and top-level capabilities over the last two decades are outlined. Technology and performance enhancements are then described in terms of importance to RF environment simulation fidelity. The thorny question *'Is perfect simulation ('emulation') of the operational air RF environment realistically achievable using RF simulators and is it really warranted?'* is then addressed, with reference to *why* higher fidelity is actually needed.

EW receivers and consequently simulators operate in the same technical parameter space, since all operate generally with the same RF threat environment. No requirement or numeric herein is thus intended to be associated with any specific SUT, platform or programme. Likewise, this paper does not discuss emitter databases. These are essential to SUT and simulator operation, but are nationally sensitive. Ref.6 gives an unclassified insight into database use in the EW T&E process.

2.0 KEY SIMULATOR REQUIREMENTS

This section identifies simulator requirements, purpose and benefits. It outlines test mission types and locations, discusses platforms and the EW measurement techniques used to identify and locate threat emitters, and describes the resultant attributes of simulators required to prove those systems work correctly.

https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press

2.1 Laboratory *vs* flight correlation and overall T&E affordability

For decades there has been world-wide bad press concerning EW systems and their alleged poor combat performance. In particular this criticism has been aimed at EW receiver systems and their ability to correctly identify and locate life- and mission-threatening enemy weapon systems. The origins of this oft-justified criticism, that triggered much of the effort that resulted in the comprehensive simulators now available, can be traced to the Vietnam War where the loss of aircraft to Soviet SA-2 missiles focused the minds of the EW community on higher quality threat detection and better tactics and countermeasures.

The main problem faced by the scientists and engineers of the time was the great difficulty in reproducing combat and flight test results on EW receiver systems in the laboratory for all but the simplest test cases. Even today this complex problem is not wholly resolved and this is discussed later. Of equal emphasis was and remains overall EW and T&E process affordability[3]. To fully develop a new or upgraded EW receiver system wholly by the then traditional fly-fix-fly method became unaffordable, in time and money, over a decade ago. The T&E community subsequently developed capabilities that allowed tests to be transferred, wherever possible, from flight test to aircraft ground test, to avionics/systems integration laboratories, to sub-system and equipment test laboratories, to *validated* modelling. As simulator, laboratory and anechoic chamber capabilities have grown, the need for expensive EW flight testing has reduced.

2.2 Simulators in the EW T&E process

Simulators provide controlled and repeatable RF emitter environments, primarily for developing SUTs and proving their compliance to specification via laboratory and aircraft ground/flight trials. Threat DF and ID are the two cardinal parameters to be proven, where DF has moved from azimuth-only 20 years ago, through azimuth and elevation 5-10 years ago, to the most recent developments towards precise and fast geo-location from long ranges.

It is useful to understand what is meant by 'emitter' and 'threat emitter' in the context of simulators. An emitter is a military or civilian RF-generating system on land or on an air, sea or land platform. It is usually a radar- or radio-based system, e.g. air traffic control radar, ship's search radar. A 'threat emitter' is one or more of the radars associated with a weapon system that might pose a hazard to one's own platform. A good example is a surface-to-air missile system's search, target tracking and fire control radars, see Fig. 3. Ref.4 gives a description of such threats and Table 2.3 of Ref.7 provides an indication of their RF parameters. The ability of an EW system to quickly and accurately determine the ID and location of threat RF emissions incident on the SUT's antennas is crucial to mission success and platform and crew survival. This survival is usually enabled through engagement of optimal tactics and threat countermeasures, e.g. RF jamming, flares, CHAFF and directed infra-red countermeasures.



Figure 3. SA-6 surface-to-air missile system. (© Reproduced with permission of Jane's Information Systems).

Terms used to describe the above 'proving' process, generically known as the 'EW T&E process', include validation, qualification, verification and certification. The precise definitions of these terms, which can vary between and within countries, and the interaction and overlap between activities conducted under each term are outside the scope of this paper. Whilst EW T&E processes vary between countries, many aspects are similar. Readers wanting a better understanding are referred to *'Electronic Warfare Test and Evaluation'*.[8]

The prime simulator factors applicable to this process are:

1. Does the RF signal at the simulator output accurately represent the RF environment as would be encountered by the SUT in real life?
2. Does the SUT meet its specification when tested with the simulator?

Regarding item 1, it is important to realise that simulators need to generate 'truth' (sometimes known as 'ground truth') data in terms of RF environment, i.e. irrespective of the SUT's capability to measure that environment. The fidelity level necessary to support this is discussed in Section 5.0. This truth data is then compared to measured data from tests/trials. Error budget analysis and application of pass/fail criteria completes the proving process.

Simulators are also used for in-service support of platforms, including mission data validation pre-combat, aircrew/groundcrew training and problem evaluation. Their use during design, development and in-service support is elaborated in Section 2.4.

To support the above, simulators contain various modelling elements with their computing component. That component's outputs are used to digitally control the simulator's RF output components. Figure 4 gives a schematic of a generic simulator, with the main features of the above modelling elements.

Simulators also have to produce operationally realistic quantities of RF emitters, with consequently high pulse densities, in real-time and with high accuracy and repeatability. Together, these needs combine to create an extremely demanding computing, digital and RF technology requirement that remains challenging.

2.3 Benefits of simulators

The primary benefits of simulators are:

1. **Reduces cost and provides more repeatable testing than by flight trials.** Maximises cost-effective execution of SUT performance verification tests to support contract compliance. Optimises overall test repeatability and efficiency when test stimulus commonality is achieved between EW equipment supplier, platform/system integrator and military user.
2. **Finds problems earlier in programme,** in the laboratory and chamber, yielding faster and less costly fixes than for those

KEY COMPONENT	CARDINAL FUNCTION	MAIN FEATURES
RF EMITTER MODEL	PULSED & CW RF WAVEFORM GENERATION	*SIGNAL* PARAMETER DEFINITIONS, e.g. • FREQUENCY, PW, PRI, POWER • MODULATION PARAMETERS
	TRANSMIT ANTENNA CHARACTERISTICS	*EQUIPMENT* CHARACTERISTICS, e.g. • BEAM AND SCAN PATTERNS, RATES
PROPAGATION & ATMOSPHERIC EFFECTS MODEL	SIGNAL TRANSMISSION EFFECTS BETWEEN SUT ANTENNAS & EACH EMITTER	• ABSORPTION ATTENUATION, DUCTING • SURFACE TYPES (SEA STATE & TERRAIN ROUGHNESS) • MULTIPATH (SEA, LAND, OTHER PLATFORMS) • POLARISATION EFFECTS • TERRAIN SCREENING/BLOCKING • EMITTER-SUT RELATIVE GEOMETRY • DYNAMICS OF OWN PLATFORM & EMITTERS
SUT ANTENNA & RECEIVER MODEL	SUT & HOST AIRCRAFT EFFECTS	• ANTENNA PATTERNS & DISPOSITIONS ON AIRFRAME • DF TECHNIQUES, e.g. PHASE COMPARISON, TDOA • RECEIVER THRESHOLD MODELS

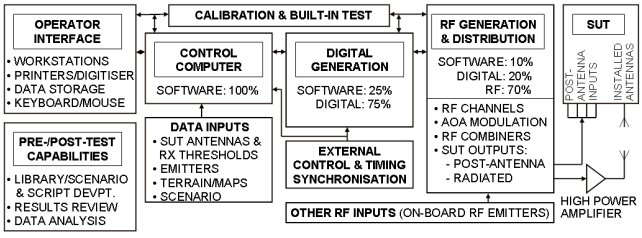


Figure 4. Simulator schematic and key modelling elements.

https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press

problems discovered later in the programme. Increases SUT maturity at the earliest time in the programme and minimises over-run risk. Discovering >90% of problems via laboratory and chamber testing is nowadays a common goal.

3. **Reduces risk of technical under-performance** on SUT delivery to military user.
4. **Reduces schedule risk** – design and development through to Operational Readiness Statement.
5. **Enhances operational support:** assists operational evaluation prior to service release. Enables high fidelity RWR/ESM/ECM mission data validation, tactics and RF countermeasures optimisation, and realistic training and mission rehearsal prior to combat use. Increases confidence in EW system performance under combat conditions. Enhances ability to repeat, isolate and resolve operational problems via highly controlled test conditions.

Useful examples of simulator usage and benefits are covered in a number of publications[8,9,10].

2.4 Test mission types and content

Simulator requirements can be derived from a consideration of the SUT's specified performance, SUT-specific threats, other RF emitters and test missions. Table 1 shows an approximately chronological series of test missions *vs.* locations for newly developed or upgraded EW systems. It is relevant to note that aspects of each are relevant to industry, whose interest is predominantly in successfully complying with the SUT's specification verification matrix (and thus getting paid), and to the armed forces, whose primary focus is mission success, maximum survival probability and minimum operating and life cycle costs.

Table 1
EW test mission vs test location

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

Table 2
EW receiver system tests

Probability of Intercept/Detection	Emitter Identification (correctness; lack of ambiguity)
Time to correctly ID emitters (threat and non-threat)	Threat DF/AOA accuracy
Threat range/pseudo-range (accuracy)	Threat location (Circular/Elliptical Error Probability)
Threat prioritisation (correctness of)	False Alarms (quantity and rate)
Missed alarms and non-detection/display of threats	Defensive/Offensive sub-systems' cueing/triggering

Simulators are configured for SUT testing in two ways, directly coupled and radiated. In the first case the SUT antennas are removed and the RF signal is injected into the SUT's antennas' cables, with the simulator containing a receive aperture/antenna model for each SUT antenna. This method is also known as 'post-antenna injection'. In the radiated case the RF signals from the simulator are not processed by the aperture/antenna model, but are routed to high power amplifiers and thence to transmit antennas within the anechoic chamber or on the flight test/trials range (aka open air range [OAR]). Figure 5 shows an aircraft undergoing such testing in BAE SYSTEMS' EW Test Facility, with a transmit antenna stack inset.

Table 2 shows the primary areas of interest when testing EW receiver systems with simulators.

2.5 Platforms, SUTs and measurement techniques

Simulators are used to test EW receiver systems on a wide range of platforms, e.g. unmanned air vehicles, fighters, helicopters, bombers and larger aircraft. In the case of laboratory-based tests, a large part of a simulator is common across platform types. The area that invariably differs is the SUT interface. Primary differences are:

1. Frequency band(s).
2. Antenna types, gains, polarisations, numbers and disposition on the platform.
3. Signal handling capability, aka 'pulse density', for continuous wave (CW) and pulsed signals.
4. Receiver CW/pulsed emitter detection (sensitivity) thresholds.

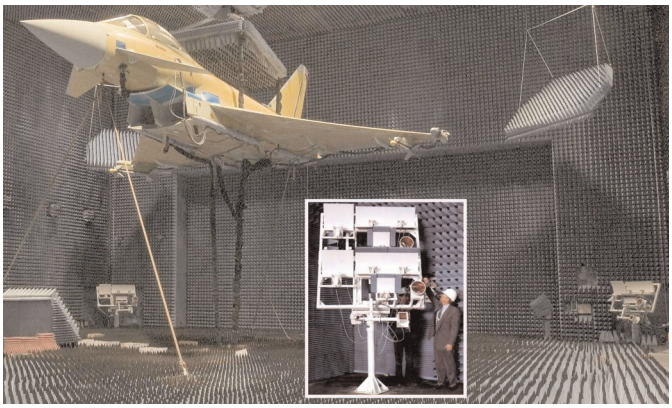


Figure 5. Radiated EW tests in anechoic chamber.
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Table 3
Emitter DF and location techniques

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	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)	<2º	Complex, especially on aircraft, and needs large platform for highest accuracy

5. Measurement techniques utilised by the SUT's receiver and processing elements.

With the exception of item 5, these are discussed later in this paper. Whilst detailed discussion of various direction finding and emitter location techniques is adequately covered elsewhere, e.g. Ref.7, the main techniques are summarised in Table 3. It is of note that, with the advent of 'digital receivers',[11] SUTs are being developed that use combinational techniques, e.g. time difference of arrival (TDOA) with frequency difference of arrival ('differential doppler'), thus optimising overall performance by mitigating individual techniques' ambiguities and other limitations. In pursuit of the militarily high priority precise geo-location of threats, multi-platform solutions are under investigation in a number of countries. Despite the need for high bandwidth data-links, they offer superior accuracy to single platform solutions.

Types of SUT antennas include spiral (single and dual-polarisation), log-periodic and horn (static or with/without spinner). Figure 6 shows an example of the most commonly used EW antenna, the cavity-backed spiral, in this photograph a dual circularly polarised version.

2.6 Resultant RF simulator attributes

Consideration of the requirements of Sections 2.1 to 2.5 yields a cardinal point simulator specification that can be tailored to the SUT to be evaluated. Table 4 gives a view of typical specification elements for a generic simulator, as gleaned from open-source marketing material, e.g. supplier web pages[12,13] and market surveys done by this author. Whilst the table clearly indicates the complexity of a modern simulator, it is not intended to be definitive or exhaustive. A typical cardinal point specification is 10-20 pp. whereas a 'best-practice', detailed contract specification for a large simulator is 140-170 pp. As this suggests, much detail is required to precisely define what is meant by the terms in Table 4.

3.0 RF THREAT SIMULATORS – THE PAST TWO DECADES

This section outlines the origins of simulators and differentiates between the size of simulators in terms of the primary differentiator (other than SUT interface and RF source type) – number of RF channels. For large, 'many-channel' simulators, the subject of this paper, the limited number of companies and models commercially available during the last 20 years is explored.

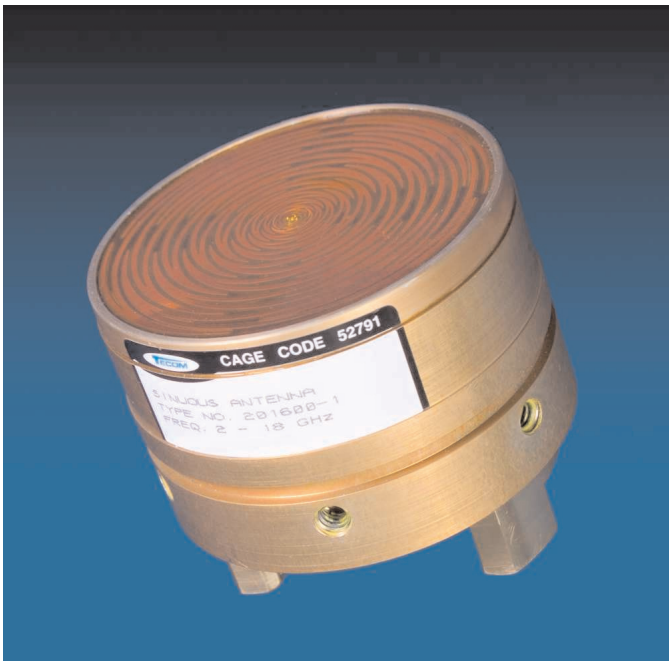


Figure 6. Typical EW receive antenna.
(With permission, TECOM Industries, Inc).

3.1 Origins of RF simulators

Prior to the advent of modern day commercially available simulators in the late 1970's, threat emitter simulation was realised at the simplest level by the use of a CW signal generator, a voltage-controlled oscillator (VCO), feeding either the SUT (post-antenna) or an amplifier and antenna for free space irradiation of the SUT's antennas. Addition of a microwave PIN† diode modulator, driven by a pulse signal generator, allowed simulation of simple pulsed signals – usually only in terms of PW and PRI. Main drawbacks, although state of the art at the time, were: only a single emitter could be simulated at a time; limited modulation schemes; limited frequency accuracy/repeatability; coarse frequency resolution; and relatively poor noise performance. Most SUTs of the time used the four-port amplitude comparison technique and so a simple receiver model was used in early simulators to generate the required four RF signals. The introduction of commercially available synthesised signal generators improved this situation, but overall the capability was very limited compared to today's simulators.

In the 1970s the only commercially available multi-channel simulator was believed to be the Antekna Standard Threat Emitter System, but this too was similarly based. In 1977 the US Naval Research Laboratories started development, in conjunction with Amherst Systems Inc (which was founded in 1975) of the Tactical EW Environment Simulator (TEWES). This was the first time-shared, highly multiplexed, dense environment simulator. The first production TEWES unit was delivered in 1980, TEWES technology was formally transitioned to industry in 1981 and was developed into the 1983 Advanced TEWES – the forerunner of the CEESIM first delivered by Amherst that year.

EW receiver manufacturers have generally developed bespoke single and multi-source simulators based around the above basic building blocks to support internal product design and development processes. Little information was and is openly published on the capabilities of these bespoke simulators, whose use prevails but has been rapidly supplanted in the last decade by powerful simulators now available.

† P-type – Instrinsic region – N-type semi conductor.

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Table 4
Top level cardinal point specification

Top level requirement	Typical range	Comment
Number of platforms and emitters	128-1024 platforms; 128-1024 emitters; up to 1024 simultaneously active emitters *at RF*. Can have many more at digital level, *e.g.* >10k.	Simultaneous emitter capability at RF constrained only by simulator's digital/RF assets; maximum reported capability 8192 but none known in the field with that many simultaneous *at RF*.
RF channels/sources	4-22 channels, usually of mixed types (VCO/DTO/FLO/Synthesiser) and banded in ranges typically 0·5-40GHz, with 0·1-100GHz typical in supplier information.	Modern simulator architectures can cater for up to 64 channels. Synthesisers for CW and High PRF PD emitters.
Pulse density	0·5-8 Mega-Pulses Per Second (MPPS). 1 MPPS = typical all-up pulse density, independent of scenario and RF channel frequency banding. Maximum reported is 8 MPPS.	0·5-1·6 MPPS advertised per RF channel. Average ~0·3 MPPS/channel achieved for real-world emitter scenarios. Pulse 'burst mode' available, giving ≥10 MPPS, but does not represent real world emitter.
RF emitter types & modulations; scan types	All general modulations: Amplitude, Frequency & Phase (AMOP, FMOP, PMOP), Pulse Doppler, hopper (agility), stagger, jitter, bursts, groups, periodic, synchronised. All scan types, including electronically scanned.	High-fidelity intra-pulse modulation for Unintentional Modulation on Pulse (UMOP) – simultaneous AMOP/FMOP/PMOP at 8-12·5ns sample rate.
Pulse Repetition Interval (PRI) & Pulse Width (PW) ranges	PRI: 1 μs - 100ms; PW: 25ns - >32ms	Precision PRI timing now available to simulate individual emitter crystal clocks.
Frequency/amplitude accuracy	Frequency: ±1 MHz (VCO/DTO/FLO); ±5 kHz (synthesised source). Amplitude: ±0·5dB	Frequency accuracy dependent on RF source type and frequency sub-band.
Channel re-tune time	≤1·5μs for DTO/FLO and High-Speed Synthesisers	Channel hop time from one frequency to generate emitter at another, including settling time.
RF output power; noise floor; dynamic range; spurious & harmonics	0 to +10 dBm for direct injection mode, with better than –85 dBm/MHz noise floor. Dynamic range up to 90dB @ 0·25 dB resolution. –60dBc spurious, harmonics and phase noise. Higher (kW) powers using amplifiers, but with increased noise.	Modern, more sensitive SUTs lead to: Lower power outputs (typically –20 dBm) for direct injection, due to Signal-to-Noise Ratio (SNR) trade-off. Pulse-off noise level for direction injection mode better than –100dBm/MHz.
AOA ports, emitter and SUT Rx antenna/aperture modelling	8-50 ports. 0·5-3·0M data points per Rx antenna. ~6k data points per 2D (elliptical) emitter antenna, with 0·25dB amplitude resolution. Dynamic modelling of transmit/Rx polarisation	Ports depends on number of SUT antennas. Instances of >150 ports exist. Rx antenna patterns can be 'calculated' or 'measured.' 3D models now available for emitter antenna patterns (~5M data points per antenna).

3.2 Many-channel simulator suppliers – past and present

Simulators come in a wide range of sizes but, as witnessed by current supplier offerings, there are four main types. 'Pico-' units, e.g. Pico-AMES, are primarily for desktop use; 'Micro-' units, e.g. Micro-Radar Signal Simulator (RSS), are transportable and are well-suited to flight-line use; 'standard' units, e.g. CEESIM-MkN, are full-sized simulators, for laboratory and chamber use; and range simulators. In each case the basic technology is the same, only the capability and price vary. The primary difference between the first three types is the number of RF channels.

In practice, when considering what constitutes a 'many-channel' simulator, there are two main boundaries in laboratory/chamber simulator size for the design and development of modern EW suites – at ≥5 and ≥10 RF channels, independent of source type. Figure 7 shows numbers of channels per simulator for all data currently available to this author.

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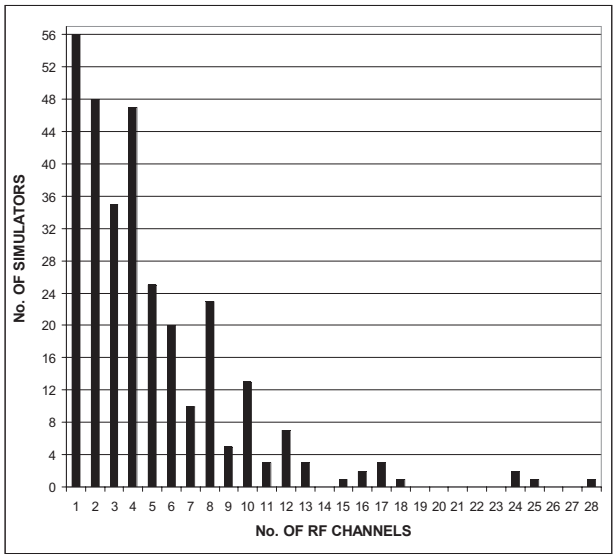


Figure 7. Quantity of RF channels per simulator.

To give the reader a perspective of the scale of many-channel simulators:

- Advanced Dynamic RF Simulator (a CEESIM-MkN), used for laboratory testing the F-22A 'Raptor' aircraft's EW suite, has 6 synthesised RF channels, 156 antenna ports, is 7·3m wide × 2·1m high, weighs 45,500kg and takes 40kVA of prime power.[9]
- That used for laboratory and chamber testing of the Typhoon's EW suite has 11 RF channels.
- The CEESIM capability of the original Benefield Anechoic Facility (BAF), i.e. before its 'Electronic Combat Integrated Test' upgrade, was 22 RF channels.[14]

Over the last two decades there have been few commercial suppliers of simulators, especially of the 'many-channel' type. This author has conducted a number of simulator surveys over the last 21 years and, in conjunction with surveys conducted by the *Journal of Electronic Defence,*[15,16,17] a good picture of the limited number of suppliers of many-channel simulators emerges, see Table 5. This table may be incomplete since not all recipients responded to the surveys. Also, it was determined by this author that some suppliers either did not produce for the open market or only supplied to their own national defence agencies and their contractors.

Some suppliers have either left the market or discontinued simulators since the 1970's, although some types remain in operation. In addition to ownership changes and model retirements indicated in Table 5, such companies and/or simulators have included Marconi Instruments (bought by IFR Systems 1998; sold to Aeroflex 2002); Walmore; PEER (Programmable Electronic Environment Replicator); and Agilent's Frequency Agile Signal Simulator (originally by Hewlett Packard).

4.0 TECHNOLOGY AND PERFORMANCE ENHANCEMENTS

This section discusses changes in simulator technology and performance. Driving requirements are described and enablers outlined. There have been few major technology or performance steps during the past 15 years; rather there has been a continuous and sustained improvement in performance.

Table 5
Many-channel simulators amd suppliers

Supplier	1991-3	1998	2001/2	2006
AAI Corp.	AN/ALM-234 (1986)	AN/ALM-234	X	X
Amherst→Comptek Amherst→NGAS Inc.	CEESIM 8k (1991)	CEESIM-8k	CEESIM-MkN (1999)	CEESIM-MkN
ASDI→ Comptek, ASD→ Comptek Amherst→ NGAS Inc.	AMES-II (1985)	AMES-II	AMES-II	AMES-III (2003)
CAL corp.	TASS	X	X	X
Antekna→Intek→Litton→S ^{3} Inc. →CSA Inc. →Cubic Corp.	X	X	HIDESS	HIDESS
Elettronica	RFEG (AMES-II RF/digital)	RFEG	X	X
Elisra Electronic Systems	X	X	REAS-REGEV	X
EWsT (+ EW/ECM ex-Anaren Microwave Ltd.)→ Herley Industries Inc.-EWsT	RSS7000 & 7500 (both 1993)	RSS7500	RSS 8000 (2001)	RSS8000
Excalibur→DRS EW & Network Systems (Canada) Ltd.	TS-100	TS-100	TS-100	TS-100+
Reflectone UK Ltd.→BAE SYSTEMS→CAE	X	EES600	EES600	X
S.T. Research	RA-600, 600R	X	X	X
Thales - Omega S.A.	X	X	ABYSS	X
Tracor→Marconi Electronic Systems→BAE SYSTEMS	MRES	X	X	X

4.1 Change drivers and enablers

The primary drivers for simulator performance enhancements can be summarised under three headings:

4.1.1 Increasing performance and features of threat radars to be simulated

The overall threat environment, in terms of potential numbers and type of radars, frequency range and distribution, modulation types and CW/pulsed signal density, has grown over the last two decades. Threat radars have evolved during this time, with many new features. This trend is likely to continue to assure radar advantages, whilst being resilient to EW jamming and being increasingly difficult to detect using EW receivers. Simulator-relevant enhancements include expanded frequency range, advanced modulation schemes, electronically scanned (multi-beam) radars and low probability of intercept/detection (LPI/LPD) techniques, e.g. spread spectrum.

4.1.2 Increasing sophistication of EW systems being evaluated

To assist combat survival in modern threat scenarios, EW receiver designs have had to develop to match the above radar developments. This has been reflected in elevated RWR/ESM requirements[1,11,18] such as:

- expanded frequency range from the traditional 2-18GHz to the modern ≤0·5 to ≥40GHz.
- better detection sensitivity (to see threat main-beams and side-lobes at longer ranges).
- more and enhanced measurement and analysis techniques (for improved DF, precision location and ID performance), including:
  - ➢ simultaneous phase and amplitude measurement.
  - ➢ scan analysis.

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- side-lobe recognition (detection when not in the threat's main beam and detection of LPI/LPD radars).
- PRI Doppler (fine-grain PRI/frequency shifts as a function of emitter-SUT distance and closing rate).
- simultaneous horizontal and vertical polarisation detection at the same aperture.
- measurement of UMOP.

- better handling of dense signal environments, i.e. above the 'rule-of-thumb' 1MPPS threshold.

Generally there has been an upward movement in EW receiver capability that has led to a blurring of the boundary between RWR and ESM, and where, with the sustained rate of technology improvements, high-end ESM capability now approaches ELINT-grade receiver performance. Such improvements have been enabled by extensive and ongoing R&D world-wide on passive sensor technology, DF measurement and ID techniques, digital signal processing and high-speed analogue-to-digital converters.

It is noted that handling a greater number of threats simultaneously is no longer the key performance and cost driver, rather it is a greatly increased diversity of techniques targeting precise geo-location of threats.

4.1.3 The need for increased EW T&E cost-effectiveness

Affordability has always been a key factor for defence customers. In recent times it has become as important as platform and equipment technical performance. The last decade has seen defence ministries driving ever-harder deals with industry – better military product performance at lower cost.[3] During this period there has, in a number of countries, been a transition from cost-plus contracts to fixed price, installed performance demonstration contracts with strict performance verification and acceptance criteria. There has also long been the need to significantly reduce the historically poor schedule, cost and risk performance of EW programmes world-wide. As T&E is a significant part of the overall EW budget, a key requirement has thus been to conduct more and better EW T&E with diminishing budgets. Throughout this period simulators have played an increasing role in enabling much of the required SUT performance to be proven in the laboratory and chamber, rather than by expensive flight test.

With the continuing drive for cost-effectiveness, against a backdrop of tighter national defence budgets, comes a need for better threat simulation fidelity, to enable closer correlation between tests in the laboratory, anechoic chamber, open air test sites, OARs and combat operations. This would enable optimum EW T&E cost-effectiveness.

Another important facet has been the move from customers considering primarily the initial purchase cost in selecting a platform (and hence EW equipment), with less emphasis on running costs, to making that decision holistically, based on 'life cycle cost' (LCC) considerations.

4.1.4 Enabling advances

The core simulator technologies of digital processing, RF signal generation and computing power have, over the years and to a large degree, kept pace with the above challenging requirements. The main technology benefit to simulators during the 15 years has been the reduction in semi-conductor component size, which has enabled a sustained and continuing increase in computing power and faster switching/clocking times for digital/RF components. Figure 8 indicates this continuing trend.

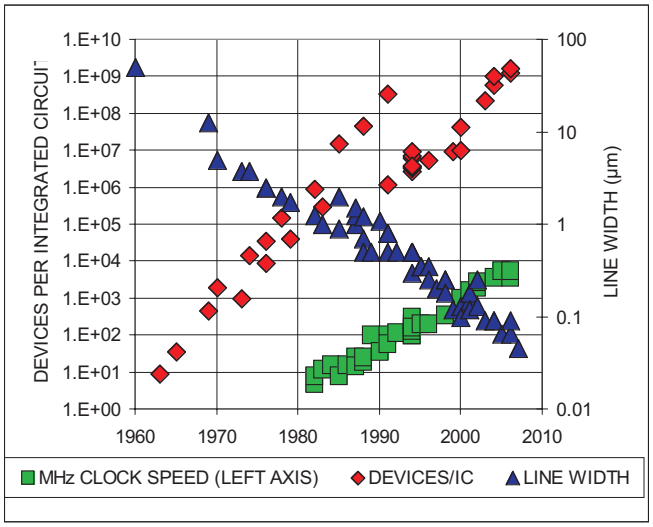


Figure 8. Circuit technology trends.

4.2 Enhancement descriptions

The main enhancements of the last 15 years are now described. Not all capabilities are available in all simulator types and models, although most are now available in larger simulators, e.g. CEESIM-MkN, see Fig. 1, RSS8000† and AMES-III, see Fig. 9.

This author is most familiar with the CEESIM and AMES products, more so with the former, to whose development he has contributed for more than a decade. Whilst the remainder of this section is largely generic, the reader may thus find some bias toward the CEESIM, which is arguably the best known example of simulator technology evolution over the last 30 years. The CEESIM has a solid history, with first of model deliveries after the 1983 original: -64 (1986), -1000 (1986), -256 (1989), -8k (1991), portable (1996) and -MkN (1999). The AMES line, formerly CEESIM's main competitor, has a similar pedigree: -I (1981), -II (1985) and -III (2003). Together, these three types form the largest community of commercially available simulators, with customers world-wide. Independent of model, RF simulators sold or on order for these types are: CEESIM (155), AMES (135) and RSS (100).

Un-prioritised enhancements are described below under the most relevant one of four headings, covering the three modelling elements in Fig. 4 and 'Other enhancements'.

4.2.1 Emitter modelling

4.2.1.1 Fully complex emitters and environment realism

The earliest simulator requirements for emitter generation comprised merely PW and PRI. Computing power, digital and RF component limitations prevented production of large numbers of fully complex emitters, i.e. with full modelling of all necessary RF parameters. The result was simulators with the capability to generate a few so-called 'foreground' emitters along with larger numbers of 'background' emitters. The latter did not have full parameter space modelling and could have pulses dropped at time of contention with 'foreground' and other 'background' emitters.

Nowadays, many-channel simulators of the type emphasised in this paper can produce up to thousands of fully complex emitters at the digital level. Inevitably, the ability to generate these emitters at RF is limited by the number of channels available, the channel pooling capability and the SUT's sensitivity to dropped pulses. This has

† Radar Signal Simulator model 8000, by EWsT, a Herley Industries Inc. company based at Farnborough, UK.

https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press



Figure 9. RSS8000 and AMES-III.

enabled significantly better representations of operational RF emitter environments than before. Pre-defined scenarios and man-in-the-loop scenarios can be run, with pre-scripted threat engagements or ones based on weapon system engagement models within the simulator. It is now also possible to include civilian radar emitters, RF jammers and 'third party tracking', where the emitter tracks another platform in the scenario and the SUT hardly ever or never sees its main beam.

4.2.1.2 RF source improvements

The relatively noisy original VCOs were overtaken by digitally tuned oscillators (DTOs), when SUT improvements enabled them to see noise characteristics of the earlier devices. DTOs have evolved, especially since the advent of SUTs more sensitive to phase noise. Recently, frequency-locked oscillators (FLOs), which are more environmentally stable devices with better frequency accuracy, post-tune drift, residual FM and phase noise, have begun to overtake DTOs. All three source types are able to be quickly (≤1·5μs) tuned to different frequencies within their band of operation — enabling a single source to generate multiple emitters, subject to timing constraints and settling time. However, the lack of phase coherency and relatively poor frequency accuracy renders them unsuitable for accurate simulation of high-PRF Pulse Doppler (PD) radars and CW emitters.

Synthesised sources, with accuracies of ±5kHz or better are readily available, in 'high-speed' (HSS) and 'slow-tune' (STS) types. HSS's have switching speeds similar to the FLO but are very expensive, particularly as a single such channel is required to simulate *each* PD or CW emitter for the highest level of fidelity. The use of less expensive STS's is now common, but they have lower performance and are less able to simultaneously generate multiple emitters. HSS/STS unfortunately have higher noise floors than their DTO/FLO counterparts; synthesiser noise thus unavoidably dominates simulator noise performance. Modern sources can suppress harmonics, spurious signals, inter-modulation products and AM sidebands to below –60dBc.

With increased SUT emphasis in recent times on detection and correct identification of emitters at longer ranges, to aid survival and mission effectiveness, there has been greater need for testing at lower power levels than at higher ones. This has led manufacturers of all source types to improve their noise floor performance. Due to dynamic range and SNR considerations, this has also led to a general trend toward –10 to –20dBm for simulators for laboratory testing of modern EW receiver systems, rather than the previous –5 to +10dBm.

To enable users to obtain simulators that are able to fully exercise the signal densities of EW receivers by test, rather than by the commonly used technique of extrapolated test results via prediction or modelling, there is a need for cheaper RF sources of all types. R&D targeting this goal is understood to be in progress.

Until recently source performance and cost has meant multiple sub-banded channels to cover a wide frequency range. Technology advances and LCC improvements have made wide-band sources of all types viable, e.g. 0·5-18GHz, 2-18GHz, with the additional benefit of better scenario generation flexibility.

4.2.1.3 RF pulse shaping

The RF sources listed above have the fundamental limitation that pulses generated are essentially square-wave, see Fig. 10. Real radar pulses, themselves rarely rectangular, can bear little resemblance to square waveforms when they arrive at the SUT's antennas, having been distorted by atmospheric, multipath and SUT platform-specific effects. A key SUT capability is discrimination of pulse start/stop times and peak power. For received real-world radar pulses this is never trivial. SUTs use various methods to optimise their ability in this regard and do not always use the traditional 3dB (half-power) points on a pulse for its start and stop times. Despite this limitation, for most EW receiver systems, the sources used have traditionally provided adequate simulation for T&E.

Within the last decade there have been significant developments in simulator capability to better simulate radar waveforms. The use of synthesiser-based high-fidelity intra-pulse modulation (HFIM) is now well established and yields simultaneous FMOP/AMOP/PMOP for T&E of SUTs with specific emitter identification (SEI)-type capabilities[19]. These SUTs generally work by simultaneously measuring combinations of frequency, amplitude and phase at a fast rate and then comparing the results with a library of unique characteristics of specific emitters. This process is also known as 'fingerprinting' the radar's actual waveform and is discussed elsewhere, e.g. Sections 3.2 and 4.2 of Ref.1. UMOP (within a radar's pulses) has a number of

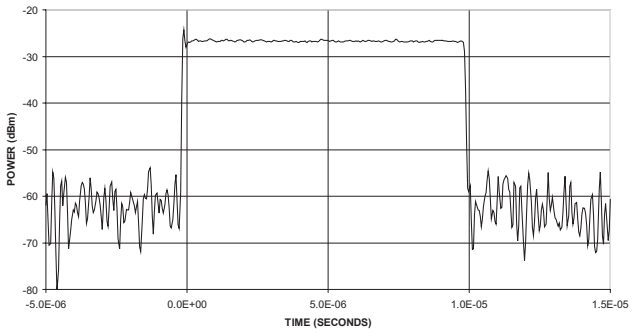


Figure 10. DTO-simulated radar pulse.

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causes related to radar source type and maintenance.[20] With the latest technology, UMOP-capable receivers are able to discriminate between radars of the same type having almost identical classical features. Other than a need for faster sampling, the only downside of the above excellent RF sources is their high cost, although research is known to be ongoing into lower cost alternatives.

4.2.1.4 Optimal use of RF resources

An ideal simulator would have many high-speed synthesised channels, each with HFIM capability. Unfortunately, this is currently unaffordable and a compromise has to be made in arriving at an adequate and affordable quantity and mix of RF channel types for a given EW T&E programme.

Given the high cost of all types of RF channels, various methods have been developed for optimising the emitter generation capacity vs. quantity and type of channels, whilst guaranteeing that simulator pulse drop-out does not increase above that which would cause problems to the SUT. This threshold varies in practice, being in the range 3-5%, but this is highly dependent upon the SUT architecture, measurement and pulse de-interleaving techniques used, and analysis software within its receiver and processing elements.

Pulse generation optimisation methods now include:

- channel pooling (pulses in a pulse train can be generated by more than one channel)
- multiple, frequency-dependent receiver thresholds for CW and pulsed signals (RF signals not generated if calculated power below thresholds)
- channel allocation to specific emitter(s)
- prioritisation of emitters and programmable 0-100% pulse drop-out per emitter
- CW fill-in mode, pulse truncation, sector blanking and de-activation/re-activation of emitters

Some methods have driven additional enhancements to constrain artefacts affecting the simulator's output, e.g. tightening of inter-port amplitude accuracy to cover the case where consecutive pulses out of any port can come from different RF channels, to prevent worsening of amplitude accuracy and consequent DF test error budget increase.

Powerful simulator tools now exist, e.g. the environment generation and analysis† (EGA) suite of software models, to enable users to pre-test analyse their test scenarios and SUT features, and thus optimise the RF channel numbers, type mix and frequency sub-banding. Figure 11 gives an example display, showing three emitters, at different frequencies and with different scan periods.

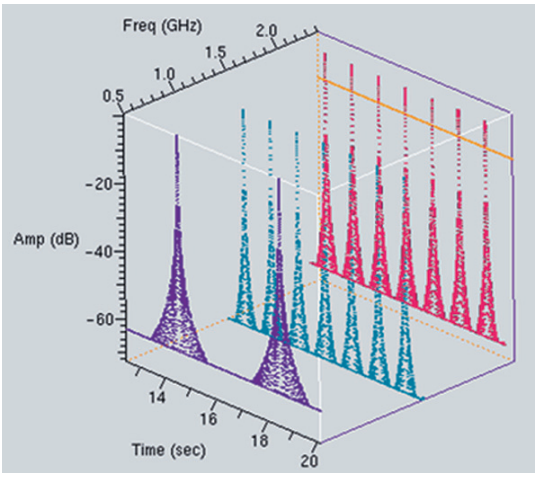


Figure 11. EGA display: 3D environment analysis. (© Northrop Grumman, Amherst systems Inc).

† EGA is a non-real time exact pulse-to-pulse simulation of CEESIM hardware.

4.2.1.5 Modelling of jammers and newer radar features

EW RF simulators, whose primary task is simulation of *radars*, are not *per se* suitable for simulating all types of *jamming* techniques. They are able to simulate some techniques, limited only by the simulator's RF source and modulator performance, but generally have difficulty with noise techniques. Solutions exist, in the form of special channels or adjunct jammer simulation capability, e.g. those by EWsT[13].

Most newer radar feature enhancements have been extensions of existing simulator capability, e.g. extended scan rates and angles; track-while-scan (including phased arrays). Simulators can thus now simulate most radar scan types[21.] Other innovations have included complex electronically scanned arrays and crystal clock count-down modelling with separately programmable clock drift rate. This latter relatively recent innovation allows testing of EW systems with the capability to identify a radar from details of its clock and allows simulation of the case where radar signals from radars of the same type on separate platforms 'walk through' each other – a strenuous test for any SUT.

4.2.1.6 Pulse modulator components

Improvements have enabled wider PW range. Faster system clocks and RF component integration have enabled finer resolution for PW (≤4ns) and PRI (better than 0·25ns). Better pulse modulator isolation has led to modulation ratios of >80dB. This ensures that, for most EW receivers and test configurations, pulse-off and inter-pulse signal levels are below the receiver's detection threshold, thus preventing possible false triggering.

4.2.1.7 Emitter antenna pattern modelling

Early simulators had coarse emitter antenna pattern modelling, known as 'key-hole', based on concentric circles of antenna gain. The user would describe the pattern by defining an azimuth range for each antenna gain value and build the elevation view by describing multiple azimuth cuts. For over a decade the much better approach of describing each antenna in terms of a single polarisation elliptical (2D) pattern, with gain *vs* azimuth and elevation cuts, has been common. Computing power limitations until recently have imposed a practical limit on the total number of data points per transmit antenna pattern, e.g. *ca.*7k points, and the simulator's ability to adequately process them at an appropriate rate. This rate can be at each geometry update, at the frame rate (AMES-III) or at the optimal pulse-to-pulse rate (CEESIM).

The T&E workaround for this has been to densely cluster available data point in the boresight region and less so over the remainder of the sphere about the antenna centre. Whilst this has sufficed for verification tests over many years, it is a major limitation in the quest to provide laboratory and chamber simulation that matches flight test/trials results.

More recent developments have included automatic interpolation between data points input by the user and the development of antenna pattern models using a 3D method. These use *ca.*5M data points per pattern and are much better at accurately generating the RF environment at the SUT's antennas than the 2D method, which is not well suited to antennas with irregularly shaped antenna patterns. Unfortunately, computing power and hardware has not yet evolved enough to allow all emitters in a complex scenario to be modelled using this 3D method. Equally important, when simulating newer radars, is the ability to allow fine angular resolution close to boresight for accurate modelling of the very narrow beamwidths now possible.

Further developments are required in this critical simulation area, including better modelling of real-world antenna systems, e.g. radiation spillover, which allows radiation at angles well outside the normal sidelobes, and random polarisation in sidelobes. Figure 12 gives an example of a radar's radiation pattern showing the spillover effect.

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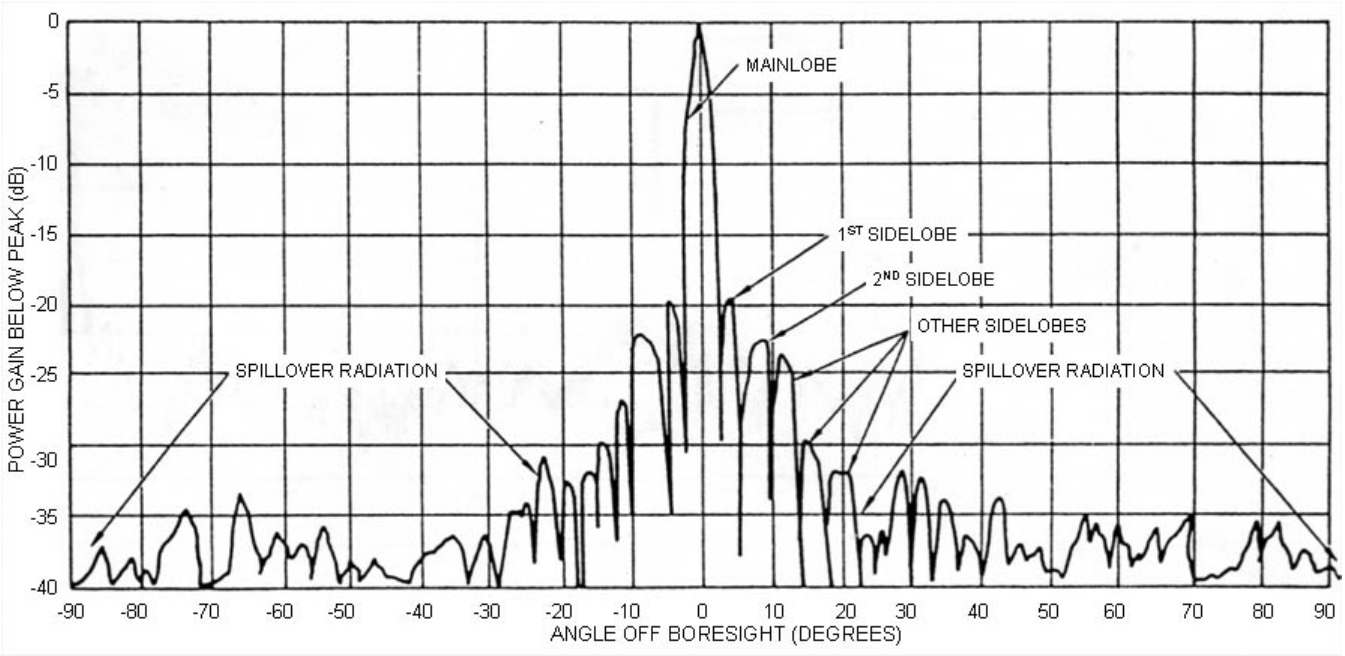


Figure 12. Spillover example (*after Benford & Swegle*).

4.2.2 *Propagation and atmospheric effects models*

4.2.2.1 *Atmospheric effects*

The earliest simulators used only a basic radar range equation[18], assuming dry air at Standard Temperature and Pressure, resulting in a path loss L as a function of distance r given by:

$$L = 20\log_{10} r \text{ dB} \quad \ldots \quad (1)$$

In due course the Friis standard radar range equation was used:

$$L = 32{\cdot}44 + 21\log_{10} r + 21\log_{10} f \text{ dB} \quad \ldots \quad (2)$$

where
r = range between transmitting and receiving antennas in km
f = frequency in MHz
32·44 dB is a constant relating distance in km and frequency in MHz

Enhancements then included frequency dependency due to oxygen and water vapour absorption, and scattering due to rainfall rates. Atmospheric ducting, i.e. refractive layers of air, usually above sea, that allow electromagnetic radiation to travel much further than would be the case in dry air, was generally introduced around a decade ago. The underpinning models used are well established, e.g. Skolnik[21] (radar handbook), Van Vleck, also in Ref. 21 (atmospheric absorption), and Kahan and Echart[22] (ducting).

4.2.2.2 *Multipath*

Specular reflections of emitter signals from the ground/sea and other platforms to the SUT, that simulator computing power limitations previously prevented, can now be modelled. Using parameters including path length difference, graze angle, surface roughness and emitter frequency, the phase angle difference can be determined. Phase angle and modulation amplitude are then used to determine signal attenuation/cancellation or amplification at the SUT antennas.

4.2.2.3 *Gaming volume, surface types, terrain modelling/masking*

Originally simulators could only simulate flat earth. An early innovation was the additional choice of areas of the earth, up to a few hundreds of km on side. For some time, simulators have been able to generate gaming volumes of between 1k × 1k nautical miles up to entire earth × 100k feet altitude. The World Geodetic Survey 1984 '4/3 spheroid' earth is generally used. In a parallel development, different surface types were introduced – land sub-types and sea states, with either the whole scenario gaming area at one surface type or using reflectivity maps.

Fifteen years ago simulators only provided simple maps, showing primary routes and geographical features, and land surface types were limited to one type per scenario. Simulators can now generate multiple sub-types within a gaming area and use map data from high grade sources, e.g. Defense Terrain Elevation Database (–1) for terrain modelling and masking of emitters, and vector maps for scenario displays. Figure 13 shows a typical scenario display.

4.2.2.4 *Platform and Emitter geometry modelling and dynamics*

To ensure correct AoA of electromagnetic waves impinging on the platform containing the SUT it is necessary to accurately model relative geometry of platform and radiating emitters. Six degrees of freedom is now standard: latitude, longitude, altitude, roll, pitch and yaw for spherical earth modelling, and *x, y, z*, pitch, roll and yaw for flat earth modelling.

For adequate testing of EW systems' ability to track threats under manoeuvring conditions, relative geometry needs to be calculated at an appropriate rate. At minimum this tended to be 1Hz in earlier times, which was adequate for a less manoeuvrable aircraft with a coarse DF, azimuth-only RWR approaching a ground-based threat radar. This rate is inadequate for the case where threat and own platform are highly agile fighters and/or the own platform has an EW receiver with high accuracy azimuth and elevation DF capability. Geometry updates should ideally be processed on a pulse-by-pulse basis for maximum accuracy, although no problems have been openly reported once a rate of at least that of the host platform's avionics databus is used. 50-250Hz is common nowadays, with cases up to 1kHz.

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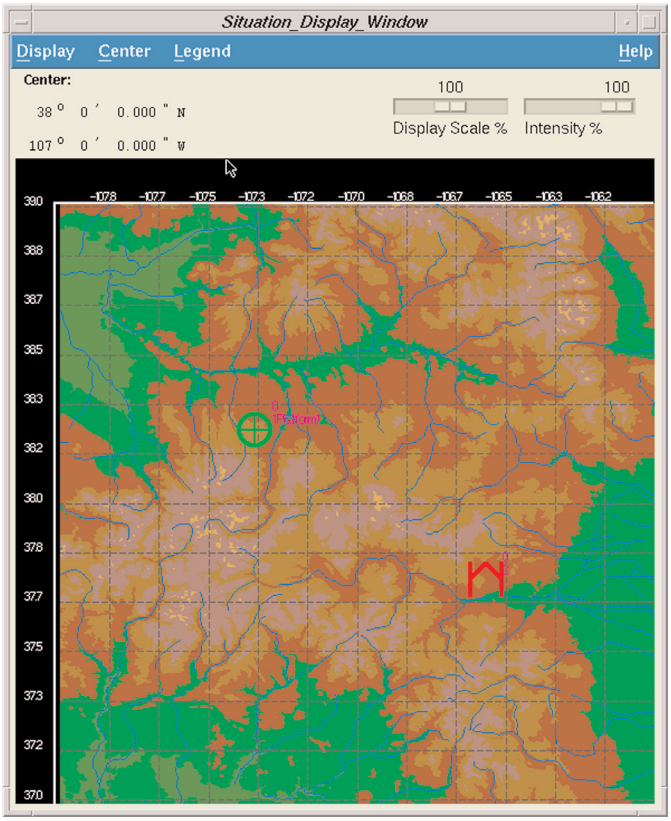


Figure 13. Typical scenario display.
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4.2.3 Platform and SUT antenna/aperture/receiver models

4.2.3.1 Receiver antenna pattern modelling

When a threat or other RF emitter signal impinges on a platform, each of the SUT's antennas is excited by a different power level, waveshape and other signal parameters, dependent upon installation details – primarily location on the platform and pointing direction. Thus the RF response, in phase and amplitude, is measurably different between each antenna element. The SUT receiver and processing elements attempt to take these installation-unique aspects into account when measuring the inbound signal, so as to minimise errors in the DF technique(s) being employed.

For direct injection testing, each SUT antenna element is modelled within the simulator. Originally this could only be achieved for a small number of antennas and then only by the 'calculated' technique, where an imaginary antenna with a single polarisation is described in terms of a set of data points covering the antenna's azimuth and elevation gains *vs.* frequency. Computing power limitations of early simulators led to far fewer points being available than would be required to adequately describe the spiral antenna seen on most SUTs. T&E workarounds involved clustering points in the frequency/amplitude/pointing angle regions of most importance, e.g. boresight. The original limitation of *ca.*0·5M data points per antenna has recently been resolved via research directed by this author and *ca.*3·0M data points, for a large number of antennas of different types, are now available. In addition, interpolation between available data points is now also available.

More recently, the 'measured' technique has become available in simulators. In this case the individual, un-installed SUT antennas and antenna arrays have their phase and amplitude characteristics measured in an anechoic chamber and these data sets are input to a simulator 'measured data' model. It is superior to the 'calculated' one, although more expensive to construct. Individual polarisation responses are modelled for 10's of thousands of measurement points *vs.* vertically and horizontally polarised sources in selected frequency ranges. A good example of this technique was on the F-22A's ALR-94 test programme, where 156 individual antenna elements were so characterised.[9]

4.2.3.2 Digitally controlled attenuators

Switchable attenuators are used primarily for transmit/receive antenna simulation, propagation path modelling and AMOP. Earlier attenuators had at best a resolution of 1dB, which is coarse for environment simulation given the additive accuracy/resolution effects of multiple components. Attenuators improved first to 0·5dB and now 0·25dB is common. Research directed by this author has shown that further improvement to 0·125dB steps would be worthwhile, enabling better representation of real-world signals.

4.2.3.3 Phase comparison and TDOA SUT techniques

Simulators originally worked with early RWRs that only used the relatively simple amplitude comparison technique. The introduction of the phase comparison technique to SUTs to achieve better DF accuracies meant simulators had to provide more ports of RF and with high phase modulation and amplitude accuracies.

The relatively recent introduction of SUT implementations utilising the TDOA technique for improved DF performance required simulators to further tighten phase and amplitude accuracies and added a new dimension – stringent pulse time of arrival (TOA) accuracy and resolution. For example, phase modulation and amplitude accuracies of ±2º and ±0·5dB respectively, and ±1·5ns TOA relative (inter-port) accuracy with 0·5ns resolution can now be achieved.

To enable accurate TDOA antenna modelling it was necessary to introduce a rectangular 'wire grid' model of the platform within the simulator, where each TDOA antenna could be placed at the correct *x/y/z* with respect to SUT 'centre', to a resolution of ≤5mm. Each antenna could then also be inclined/declined in the azimuth/elevation planes (or platform axes), representing required installation angles. Previously this 'centre', where incident power densities were calculated to, represented the co-located antennas of a traditional four-port amplitude comparison RWR installation – often found on an aircraft's tail.

4.2.3.4 Polarisation modelling

Emitter antenna polarisation modelling was originally limited to horizontal or vertical and, in the case of spiral antennas, right hand circularly polarised (CP). Simulators used a simple look-up table of coupling loss between incident electromagnetic wave polarisation and receive antennas of different polarisations, with polarisation mismatch loss fixed per scenario, to determine received power at the SUT. As threat radar technology advanced so did simulators, which introduced additional polarisations and both hands of CP. Table 6 shows a typical look-up table.

A major improvement in this area was the move to full vector modelling of the emitter and SUT, correctly taking into account relative geometry between the SUT platform and the emitters, including the polarisation modification effects of multipath from the ground and other reflectors. Figure 14 depicts orientation mismatch angle modelling. Further developments have included simulation of modern radars with polarisation diversity, i.e. those able to change polarisation on a frame or scan basis.

4.2.4 Other enhancements

4.2.4.1 Simulator control and timing synchronisation

High fidelity testing of modern integrated EW systems necessitates tightly time-synchronised RF stimulus and measurement equipment. For tests

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Table 6
Polarisation mismatch look-up table

		WAVE POLARISATION					
		VERTICAL	HORIZONTAL	RIGHT HAND CP	LEFT HAND CP	RIGHT SLANT LINEAR	LEFT SLANT LINEAR
ANTENNA POLARISATION	VERTICAL	0 dB	∞	3 dB	3 dB	3 dB	3 dB
	HORIZ-ONTAL	∞	0 dB	3 dB	3 dB	3 dB	3 dB
	RIGHT HAND CP	3 dB	3 dB	0 dB	∞	3 dB	3 dB
	LEFT HAND CP	3 dB	3 dB	∞	0 dB	3 dB	3 dB
	RIGHT SLANT LINEAR	3 dB	3 dB	3 dB	3 dB	0 dB	∞
	LEFT SLANT LINEAR	3 dB	3 dB	3 dB	3 dB	∞	0 dB

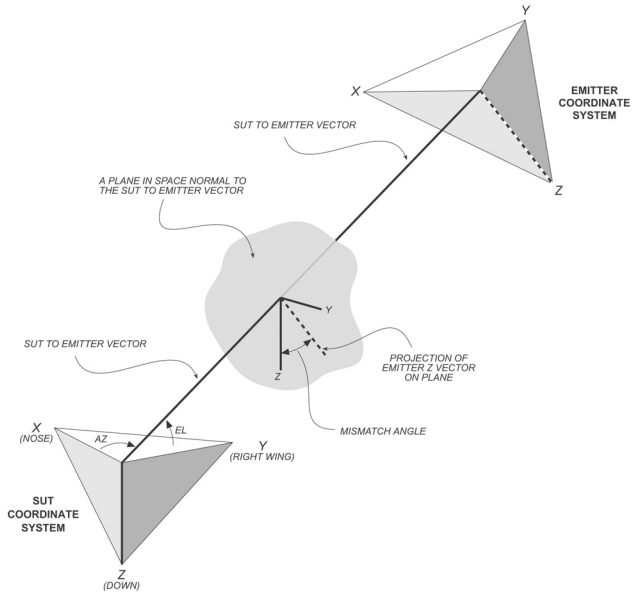


Figure 14. Polarisation mismatch vector modelling.
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where sensor fusion is also to be evaluated it is critical that all SUT sensor stimulators are time-synchronised and controlled by a master test scenario controller. During real time simulations these T&E equipments need to accept precise time synchronisation from a master clock, typically 1-10MHz.

4.2.4.2 *Support and analysis tools*

Two decades ago much data input was manual, e.g. emitter parameters, transmit/receive antenna patterns and scenario definitions, as was test data analysis. Nowadays the situation is much improved, with features in the latest simulators that ease pre-test tasks and post-test analysis. Examples include:

- User-friendly entry for emitter and SUT-dependent data and scenario development.
- Integrated antenna pattern modelling utilities.
- Simulator recording of 'truth data' for post-test correlation with SUT-measured data, e.g. the CEESIM can record 16 million, 512-bit pulse descriptor words for each scenario run.

The use of adjunct EW T&E capabilities have also been beneficial:

- ECM response measurement systems that are highly integrated with simulators, to measure and analyse RF-level test data.
- High performance data acquisition and simulation systems for stimulating/controlling the platform's avionics (including EW) and simulator, and post-test event-level data analysis.

4.2.4.3 *Availability, reliability, spares and life cycle costs*

As many-channel simulators are multi-$M complex equipments, it is not surprising that spares packs to keep these items fully operational for the required number of testing hours p.a. are expensive. This is particularly so for the intense use many of them experience. This author has done much fruitful work over the last decade targeting substantial improvements in baseline reliability, availability for testing, fault diagnosis, reduced sparing and lower LCC. Simulators can now use built-in test capability to find and report >95% of faults to the board level without user intervention.

4.2.4.4 *Calibration*

Emerging EW measurement techniques, especially those for precise geo-location and SEI, place greater technical requirements on simulators – better frequency, amplitude and phase accuracy, and greater stability and repeatability. This has led to greater emphasis on simulator calibration. Unfortunately, calibration times generally increase with increasing SUT measurement technique complexity, although various enhancements have provided some mitigation. The use of vector network analysers for calibrations, rather than power meters alone, is notable and results in halving of times for some calibration types. For SUTs with many antennas this can yield an order better calibration time, e.g. 500 phase ports in ten hours. Despite these enhancements, reducing calibration times remains a challenge.

5.0 SIMULATION FIDELITY – THE QUEST FOR AFFORDABLE EMULATION

This section defines 'fidelity' and other terms relevant to RF threat simulation. It examines how much further up the fidelity curve, as a function of test mission, is worthwhile. The reality of an affordability boundary is discussed and enhancements suggested.

5.1 Definitions

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

Nowadays terms such as 'model', 'simulation/simulator', 'emulation/emulator', 'replication/replicate', 'surrogate' and 'hybrid representation' often have multiple meanings, dependent upon nation, agency, technical sector/domain, topic/aspect/item of concern and stage in the platform/equipment life cycle. In some countries references exist to aid clarity of this multiple usage, e.g. Ref. 23, but these are not international standards *per se*.

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

- ***RF emitter simulation:*** Imitation, at RF, of the real-world characteristics and behaviour of one or more RF emitters, to a given level of fidelity. Note: Simulations/simulators are usually more cost-effective than using real threat weapon system radars for most test missions.
- ***Simulator fidelity:*** The measure of the quality of RF emitter simulation when compared to the real emitter, for all those

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spectral, spatial and temporal aspects relevant to the simulator's use in EW T&E.

- ***Emulation:*** Highest fidelity simulation, where a perfect EW receiver could not discriminate between the emulation and the real emitter. Note: Emulations/emulators are useful where the use of the real item is either not necessary or is undesirable.
- ***Verification:*** The process of determining that an EW receiver system, when tested using a threat simulator incorporating threat emitter models, meets its contractual specification.
- ***Validation:*** The process of determining whether the:
  - simulator's output, when programmed with threat emitter models, is adequate for its intended use in the T&E process.
  - SUT, when programmed with theatre-specific Mission Data, correctly identifies and reacts to real/simulated threat emitters
- ***Accreditation:*** The process of determining whether a simulator's rendition of threat emitters is suitably realistic, robust and credible.

5.2 Threat simulation fidelity

Threat simulation fidelity is dominated by two factors – threat emitter characteristics programmed into a simulator and the simulator's capability to translate those characteristics into a faithful representation of the RF signals that would be received by the SUT's antennas when radiated by the real threat under combat conditions. As with any simulation, a threat simulator's capabilities need to be fully understood in terms of the verification, validation and accreditation (VV&A) processes for modelling and simulation,[23] and for SUT performance verification and validation. Table 7 depicts VV&A from a threat simulator standpoint.

Various methods are used to confirm (or 'validate') the fidelity of a simulator's rendition of threats. National methods vary but the US one, described in Ref.24, is a good example. CROSSBOW (Construction of a Radar to Operationally Simulate Signals Believed to Originate Worldwide) is a tri-service technical agency established for the common development of EW RF simulators. It assures that simulators and models are consistent with intelligence agency threat estimates and that validation procedures are being followed. It then certifies simulator-model combinations for use for specific EW T&E cases via accreditation tests. It is understood that full CROSSBOW accreditation for a single threat-simulator combination can take over 12 months to achieve.

5.3 Why better fidelity?

For over two decades the EW community has sought simulators that could provide perfect simulation of the RF emitter environment the SUT sees during combat operations. Emitter data, emitter modelling and RF source limitations currently mean that laboratory and chamber testing remains limited when testing SUTs programmed with theatre-specific mission data.[6]

Efforts are known to be ongoing to close this fidelity gap and thus provide a capability that could enable optimisation of SUT mission data and countermeasures (technical equipment and tactics), maximise the transfer of EW T&E tasks from flight to the more cost-effective and repeatable laboratory and chamber, enhance mission rehearsal capability and shorten resolution times for operational problems. In turn, these would aid maximise platform survivability against RF-guided threat systems and hence improve mission success potential and aircrew life expectancy. Also, even though simulators are much improved, further improved fidelity is increasingly important with shrinking defence budgets, to aid more cost-effective EW systems' development and in-service support.

A good example of these efforts is the correlation of OAR emitters against the CEESIM simulators[25] in the BAF. RF signals from OAR emitters were measured and compared with RF waveforms from the simulators when programmed by the traditional input of parametric data from an EW emitter database, *cf.* Ref.6 Some significant fidelity differences were noted and methods of programming the CEESIM to produce much better representations of the emitters were developed and evaluated. Fidelity enhancements included modelling of radar switching transients, additional intra-pulse modulations and unexpected anomalous behaviours. Correlation of a single emitter took one-to-four months and it was planned to continue the effort whilst feeding back information to the EW emitter database owners to aid refinement for all users.

It was noted that the desired fidelity enhancements were taxing the CEESIM performance capabilities, which is in agreement with the message of this paper concerning all state-of-the-art simulator types, and that enhancement efforts were in progress. As with this paper, the authors of Ref.25 recognised the need to balance the value of increasing simulation fidelity further against the cost of doing so. One of their conclusions for a later phase of work was to gather fidelity requirement inputs from customers, to minimise the risk of over- or under-specifying threat simulation fidelity.

5.4 The affordability boundary

It has been long recognised that achieving emulation of combat air RF environments using simulators is utopian. The combination of

Table 7
Threat simulators and VV&A

PROCESS NAME	OBJECTIVES	KEY QUESTION	PROCESS ACHIEVES	DONE BY
VERIFICATION	USE SIMULATOR TO CONFIRM THAT SUT MEETS ITS SPECIFICATION	WAS SUT BUILT CORRECTLY?	TESTS **FUNCTION & PERFORMANCE**	SUT SUPPLIER & PLATFORM/SYSTEMS INTEGRATOR
VALIDATION	CONFIRMATION THAT: 1. SIMULATOR PRODUCES ADEQUATE REPRESENTATION OF EMITTERS 2. SUT, WHEN PROGRAMMED WITH THEATRE-SPECIFIC MISSION DATA, CORRECTLY IDENTIFIES SIMULATOR-GENERATED EMITTERS	DO SIMULATOR-GENERATED EMITTERS LOOK & BEHAVE SUFFICIENTLY LIKE THE REAL THING?	EVALUATES **FIDELITY**	MILITARY, OFTEN WITH INDUSTRY SUPPORT
ACCREDITATION	CERTIFICATION THAT [SIMULATOR + THREAT EMITTER DATA] IS ADEQUATE FOR PROVING [SUT + MISSION DATA] IS FIT FOR INTENDED MILITARY PURPOSE	CAN SIMULATOR BE USED TO OPTIMISE & VALIDATE MISSION DATA FOR EW RECEIVER SYSTEMS?	DETERMINES **CREDIBILITY**	MILITARY, OFTEN WITH INDUSTRY SUPPORT

https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press

affordability, highly complex electromagnetic interactions experienced in the real world and simulator technology limitations is likely to constrain simulations to limited resemblance to the high-pulse density, confusing electromagnetic 'mush' that is often the electronic battlespace in modern conflicts.

However, with reference to the definitions above, a *perfect* EW receiver is unlikely to ever exist. Thus the question is really whether a simulator provides sufficient fidelity for the SUT to be unable to discriminate between its outputs and emitters in the real-world RF environment. This, as for other areas of avionics T&E, is a question of adequacy – there is no need to generate significantly better fidelity than the SUT can measure. In terms of adequacy, there are a number of rules of thumb that suggest T&E equipment should be able to simulate/generate/measure to an order better than the SUT can measure. Whilst often possible in the digital context, this is less easy in the RF world but modern simulators can, for most parameters, easily exceed the parameter range of the SUT. It is less easy, even given today's technology, to significantly improve on parameter accuracies and resolutions, though few problems have been reported in this area.

When using the best available emitter simulation features described in this paper, most current SUTs – when programmed with appropriate emitter libraries and other mission-dependent data – are unlikely to be able to discriminate between the simulator's outputs and those of a real emitter. However, this statement is usually only true for low numbers of emitters and limited signal densities due to simulator affordability constraints on the number and types of RF channels available. Whether it is true for operationally realistic emitter numbers and (higher) signal densities cannot be determined practically without adding further channels of the necessary type or flight testing against an OAR with the necessary assets. RF output power constraints, again an affordability constraint for laboratory and chamber testing, can likewise limit the scope of simulations.

Despite significant improvements in simulator capability to stimulate SUTs using the TDOA technique, there remains an issue for simultaneous intra-pulse modulation and TDOA, *cf.* Ref.18 Without the use of HFIM in each RF line to the SUT's antennas, it is currently not possible to faithfully model the RF environment for that case. Unfortunately, the technology solution is available, but in practice is unaffordable. Fortunately, for some SUTs this is not an issue and for others a T&E workaround can be effected that, although restrictive, appears adequate for performance verification tests. It is thought that upcoming receivers, including enhanced 'digital receivers', will be less tolerant of this limitation.

The latest simulator technology and capabilities, particularly when enhanced in line with the outcome of the BAF efforts reported in Ref. 25, appear to be at the fidelity level where more of the T&E currently done by flight testing against real threat emitters could to be executed within the anechoic chamber and laboratory environment – offering cost saving, repeatability and investigation benefits. In addition, were the more important suggested developments of Section 5.5 realised, then it is considered that an increase in RWR/ESM/ECM mission data validation quality could also be achieved, with attendant survivability benefit to platform and aircrew. Once the above simulation fidelity level has been realised, the need for any further fidelity increase will need to be cost-benefit traded to determine whether the required tests might be better conducted *via* OAR flight trials. This situation is also in line with the US Defense Modeling and Simulation Office's view on *'State of the Art in Fidelity'*.[26]

5.5 Suggested further developments

The following suggested developments, most of which are discussed earlier, are considered worthwhile. They are in addition to, but may overlap with, those resulting from efforts reported in Ref.25. Some are of greater importance to EW T&E in the near future, should the enhanced detection, DF and ID capability promises of 'digital receivers' be fully realised.

- Better transmit antenna models, including radiation spillover, random polarisation in sidelobes and appropriate interpolation between data input by the user.
- Improved multipath modelling, including that for pulse stretching and reflections from other platforms.
- Faster HFIM channels.
- Affordable solutions to limitations on intra-pulse simulation for testing SUTs that employ the TDOA technique.
- Improved noise performance synthesised RF sources (this is particularly important for multi-channel simulators used for testing SUTs with very high detection sensitivities).
- Increased parameter ranges.
- Improved calibration capabilities, reliability and fault diagnostics to aid users maximise simulator time available for testing and minimise life cycle costs.
- Enhanced pre-/post-test analysis tools.

Some of the required technologies exist for shortfalls identified in this paper, although most are either not yet 'in the field' or commonly available, due to implementation cost and/or lack of customer/user request. For example higher resolution digitally controlled attenuators than the currently common 0·125dB ones would enable usefully improved transmit antenna modelling and AMOP. 0·1dB attenuators exist, but the changeover costs for an established simulator product are appreciable.

One fidelity enhancement considered worthy of further investigation is the inclusion of own-platform effects within simulators. Installation-unique multipath and scattering of inbound electromagnetic waves prior to being converted by SUT antennas into RF current into EW receivers is not well understood. These effects are known to be highly specific to platform type, with some specific to individual platforms within the type. Effects include pulse attenuation/amplification, wave-shape distortion and polarisation changes. Some aspects have been captured *via* installed antenna/aperture modelling, but a 'platform-specific' component remains unknown.

A way ahead may be adoption of surface models used for electromagnetic compatibility, lightning strike and communications antennas' installed performance modelling, e.g. Fig. 15. The challenge would be the real-time modelling of simulated antennas positioned on a surface model with mesh sizes as small as 0·3mm (wavelength/25) for EW frequencies.

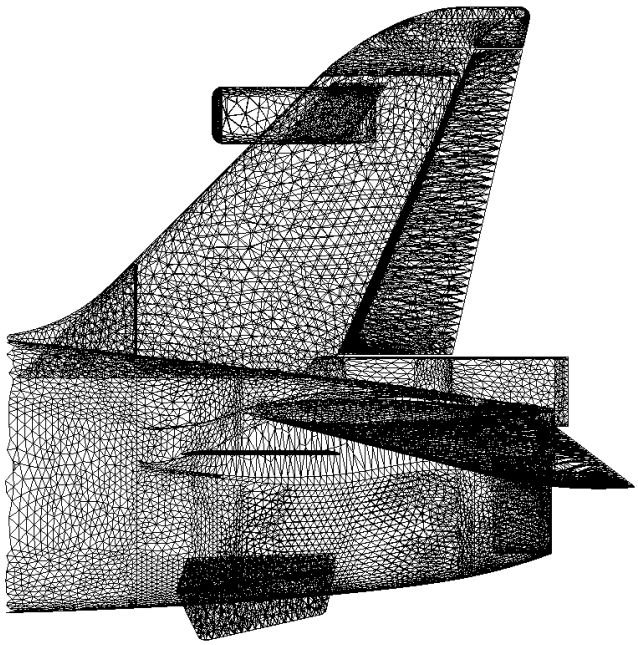


Figure 15. Typical aircraft surface model.
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https://doi.org/10.1017/S0001924000001822 Published online by Cambridge University Press

6.0 CONCLUSIONS

- RF threat simulators are essential to reduce time and expense in developing, integrating, evaluating and supporting ESM/ECM receiver and processor systems. Their use is crucial if operational performance is to be assured, mission success potential maximised and survivability optimised.
- Simulator technology has significantly matured over the past 15 years. Increases in computing power, in particular, have helped overcome earlier limitations. High fidelity simulation of operationally realistic RF scenarios is now possible, although multi-$M expensive.
- Simulators have enabled a major shift from expensive and hard to repeat development flight testing and military flight trials to repeatable and cost-effective anechoic chamber and laboratory testing. For the foreseeable future they will continue to be a powerful enabler for this ongoing transition.
- Technology mostly exists to enable emulation (perfect simulation) of RF environments seen in military operations, but this is not currently feasible. Key obstacles are:
  - Affordability, including LCC.
  - Sub-optimal models of emitter and SUT antennas, and other RF emitter characteristics.
  - Lack of suitable real-time 0·5-40GHz electromagnetic models of own-ship and other platforms for use in simulators.
  - The confounding complication of hostile, friendly and own RF jammers.
- It is thus considered unlikely that modelling and laboratory testing will ever totally supplant the need for 'installed performance' platform testing in anechoic chambers and flight.
- The high cost of emulation, if possible, is not warranted for all test missions as the current combination of modelling, laboratory and chamber tests using simulators, and flight trials against OAR assets (real and 'emulators') can provide good pre-combat confidence in EW systems' performance and effectiveness.
- With shrinking defence budgets and increasing EW system complexity, however, further improved fidelity is increasingly important to aid more cost-effective EW systems' development and in-service support.
- Developments are suggested that will also help maximise the amount of EW T&E that can be done more cost-effectively in the chamber and laboratory than in flight. Selected items could also improve mission data validation quality and hence survivability.
- Affordable simulation is very much a return-on-investment trade that should be taken at the product life-cycle level. A high-fidelity, many-channel simulator is truly a huge investment, but as it reduces live testing with the fielded platform and remains in productive use over many years, payback occurs quickly.

ACKNOWLEDGEMENTS

The author wishes to thank BAE Systems for permission to publish. Input and comments are acknowledged from P.W. Richard, Director, Electrical Engineering – EW Line of Business, BAE Systems Inc, Dr R. Andrews, Managing Director, EWsT and I. Quarrie, (formerly) Lead Test & Validation Engineer, Defence EW Centre, RAF Air Warfare Centre. Comments are also acknowledged from I.P. MacDiarmid and G. Slater of BAE Systems (UK). This paper is dedicated to the memory of Prof R.J. Simpson, a digital signal processing expert of international renown with whom this author had conducted EW R&D, who died unexpectedly summer 2006.

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