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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD CONFERENCE PROCEEDINGS 546

Challenge of Future EW System Design

(Les Défis posés par la Conception des Futurs Systèmes EW)

Papers presented at the Avionics Panel Symposium held in Ankara, Turkey, 18th–21st

NORTH ATLANTIC TREATY

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
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Theme

Electronic Warfare (EW) has emerged as a critical driving force in modern warfare. New generations of weapon systems directly impact EW requirements and strategies.

Modern combat aircraft are faced with the drastic change of a possible threat scenario consisting of a mix of Western and Eastern weapon systems. The deployment of advanced pulse doppler radar systems in A/A and G/A application augmented by extensive electro-optic capabilities, directed energy weapons (laser or particle beam), electromagnetic/shockwaves weapons requires a detailed reassessment of NATO EW processes.

The complexity and diversity of future threat scenarios necessitate changes in NATO EW system concepts, and an update of existing equipment including modifications of tactics and combinations of EW resources to improve survivability. In the five NATO Secret sessions (listed below) interaction between representatives of the military, government, academia and industry was encouraged:

— Threat scenario changes and projected requirements
— New EW concepts and architectures
— Emerging EW technologies
— EW systems and equipment
—Testing and system support.

This symposium served to review the driving factors for revised NATO EW concepts and architectures and identified key technological thrusts in EW contribution to overall combat capabilities and effectiveness in response to the threat environment.

Thème

La guerre électronique (EW) est devenue la force motrice décisive de la guerre moderne. Les nouvelles générations de systèmes d'armes ont un impact direct sur les demandes et les stratégies en guerre électronique.

Les avions de combat modernes doivent faire face à la possibilité de changements radicaux dans les scénarios de menace, qui risquent d'être caractérisés par une combinaison de systèmes d'armes de l'est et de l'ouest. Le déploiement de systèmes sophistiqués de radar Doppler à impulsions pour des applications air/air et sol/air, augmentés de capacités électro-optiques étendues, des armes à énergie dirigée (à rayon laser ou à faisceau de particules), et des armes électromagnétiques/à onde de choc exige la réévaluation complète des techniques de guerre électronique (EW) au sein de l'OTAN.

La complexité et la diversité des scénarios de menace futurs nécessitent des changements dans les concepts de systèmes EW de l'OTAN et la mise à jour du matériel existant, y compris la modification des tactiques et des combinaisons de moyens EW déployées afin d'améliorer les chances de survie.

L'interaction entre les représentants des gouvernements, les militaires et les universitaires était privilégiée lors des cinq sessions Secret OTAN prévues:
– l'évolution des scénarios de la menace et les moyens requis
– nouveaux concepts et nouvelles architectures EW
– technologies EW émergentes
– les systèmes et le matériel EW
– les essais et le soutien systèmes.

Le symposium a examiné les facteurs pilotes pour la révision des concepts et des architectures EW de l'OTAN. Il a identifié les initiatives technologiques clés dans la contribution EW aux capacités globales de combat et à l'efficacité de la réponse à l'environnement de la menace.

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INTEGRATED RADIO FREQUENCY SENSOR SYSTEM ARCHITECTURE

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ABSTRACT

Significant advances in systems integration of military avionics have mostly occurred in the areas of digital avionics, where inter-processor communication networks, standard programming languages, computer instruction sets and modular form, fit and function implementations are now being applied to new US aircraft. Cost savings resulting from the application of a common, modular architecture have only been partially applied to Radio Frequency (RF) sensors (e.g. radar, CNI and electronic warfare) through the integration of functional assets within each of these domains. Because such sensors can account for almost half the fly-away costs for a dual-role fighter (exclusive of data and signal processing), new ways to reduce this cost burden becomes extremely important.

Work performed under the Pave Pace program in the US Air Force has resulted in the preliminary design of an integrated sensor system architecture that promises to reduce the cost, weight and volume of RF functions by approximately one-half while dramatically improving the availability of the RF assets.

This paper describes the baseline architectural design for a modular building block approach for an integrated sensor system (ISS), including the key modules and network switch elements. Benefits, including significant weight savings and fault tolerance capabilities of employing this design will be described, along with the challenging management issues associated with designing, developing and maintaining integrated systems in current vertically-integrated organizations. Further, a road map for the planned development of the ISS system will be described.

1. INTRODUCTION

In tracing the evolution of avionic system architectures, it is clear that loosely coupled federated subsystems have accounted for the vast majority of designs. Hardware configurations and subsystem functionality can be closely correlated with this design approach (see Figure 1). For example, a radar subsystem often consists of a collection of "black boxes" of unique controls/displays, data processors, signal processors, pre-processors, RF receiver/transmitter and associated radar antenna componentry. The Electronic Warfare (EW) functions are implemented through a federation of individually subsystems, each with parallel functional elements being implemented. Significant progress has been made recently in exploiting the programmable feature of digital electronics to both integrate and share resource elements in order to reduce proliferation and ease retrofit and maintenance costs. Multi-function displays now allow various sensor outputs to be displayed and even overlayed on the same display surface. The subfunctional elements within CNI and EW functional elements have now been integrated and data processors now are used to control and integrate high level information across these different subsystems. We are now beginning to "time share" signal processing assets within "functional affinity groups." Common computer instruction set processors are now being replicated across the entire avionics system. However, if the architecture diagram of a modern radar, EW or CNI suite is studied, distinct, yet similar chains of signal processors, pre-processors, and RF processes can be seen. Functional partitioning and hardware implementation are still arrayed along lines of technical expertise and organizational levels established in the World War II era. It is this technical and cultural "heritage" that must be understood and overcome if the cost, performance, and availability benefits of functional integration are to be realized within avionics sensors.

2. RATIONALE FOR FUNCTIONALLY INTEGRATED SENSOR SYSTEMS

The significance of the contribution of avionic sensors to the weight, volume, electrical power, cost and failure rate for a typical multi-role military fighter (built using 1990 technology) is shown in Figure 2. Here the sensor suite is assumed to consist of a full complement of CNI capability, and A-A/G radar, EW suite, forward looking infra-red (FLIR), IR tail warning and INFRA-RED search track set (IRST). Note the dramatic impact that avionic sensors have in having almost every significant constraint normally levied on aircraft designers. (NOTE: although the above sensor complement is considered rather robust in capability, extremely "sensor-austere" designs would have to be assumed to alter conclusions drawn from Figure 2). Further, note that the information management processing (IMP) for executive, navigation, fire control, weapon delivery and health monitoring processing functions only represents a relatively small fraction of the "problem", reflecting both the results of strides made in digital technology and the past emphasis placed on standardization. Stores, system main memory (SMM), integrated flight processing (flight/propulsion control) and the pilot vehicle interface (PVI) are also modest contributors to these important constraints. Clearly, and profoundly, achieving significant progress in military avionics lies with our ability to fundamentally alter sensor design. The concepts of resource sharing, coupled with the use of advanced technologies will be the cornerstone on which weight, volume, power, cost savings and failure rate reduction will be built. We will have to seriously consider the fleet-wide use of common avionics modules, sharing of resources by mission phase, reuse of software and functionally integrated processing and integrated sensor systems. We must increase functionality without increasing the amount of hardware, using a "programmable architecture". And, just as new technologies were required to improve the performance of federated subsystems, new technologies will be required to build practicable, functionally integrated systems. Because of the need to accommodate more functions digitally, extremely high speed (in excess of one billion floating point operations per second (Giga FLOP) will be required for pre-processing and signal processing. Switching networks that operate in excess of two billion bits of data of data per second will be needed. Advanced operating systems capable of scheduling functions within microseconds will be needed. We will need, as a community, to think at higher levels of functionality - e.g. instead of thinking of a separate radio or radar functions, we must ask how sub-function can be implemented within the RF "metafunction". Hardware implementations and functional boundaries will become blurred. Hardware will be given functionality by software.

3. INTEGRATED RF ARCHITECTURE - TOP LEVEL VIEW

Figure 3 shows how advanced digital technology has been recently applied to alter the architecture of avionic systems. Note that virtually all data and signal processing is accomplished in centrally located racks containing a small family of flight line replaceable modules. Using approximately 20 of these modules types, including signal, data, and graphic processors, global memories, input-output modules and power supply modules, the entire processing function can be accommodated for the avionics system (safety-of-flight critical flight control processing modules are separate). Because of the strides made in digital microcircuitry packaging and cooling, "black box" line replaceable processor units can be replaced functionally by standard sized line replaceable modules measuring approximately 6" x 6" x 0.6", having 5 to 10 times the reliability and requiring no intermediate repair shop. Extended availability can be achieved by fault tolerance/ reconfiguration and high volume production attendant with the small number of module types which is replicated throughout the digital systems and can be used across weapon systems to further drive down costs. It is this same design philosophy which we wish to pursue with RF architectures in the future.

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Figure 4 shows a top level diagram that allows us to better observe the similarity of functions across the RF system. Building block functions that are seen to emerge include apertures to cover various portions of the RF band, frequency converters for down-converting RF to an intermediate frequency (IF), frequency converters to up-convert IF to RF, receiver electronics (filter, amplify, sort) with possibly another stage of down-conversion, pre-processing electronics and modulators. The question to be answered is whether the concepts of modularity and resource sharing that is being successfully employed for functionally integrated digital avionics can also be successfully applied to the RF domain, resulting in a practicable low cost design having equal performance superior to the federated approach.
By drawing parallels with advanced integrated modular designs for digital systems, one would desire that : (a) only a few types of functionally integrated apertures would be needed to reduce cost, inventory and maintenance problems; (b) a small modular family of frequency converters, receivers and pre-processors could be "mixed and matched" to create RF functions across the 30MHz-20GHz band; (c) a high speed switching network that allows the array of modules and apertures to be allocated in real time to enable both fault tolerance and time sharing of functions. If we are to separate unique, point designed equipment from common hardware, we must be able to "contain" unique requirements closer to the aperture and develop a "standard I/O" interface that will allow common modules to be used. RF equipment, because of its uniqueness, has not enjoyed the "infrastructure" of the digital industry relative to common manufacturing techniques, chips, etc. The RF industry often has to "build onto" what worked before. As a result, learning curve experience and reliability is difficult to achieve with low volume production and high non-recurring expenses.

Figures 5 & 6 show the common modular building blocks needed to build one example of an integrated RF system. Only 4-5 different aperture types are needed. For example, one multi-turn loop antenna type will cover the 2MHz-200MHz regime (HF and VHF functions). An Archimedes Spira antenna (multi-arm spiral antenna or MASA) provides middle band coverage to accommodate the remaining 15 (or so) CNI functions plus portions of the EW band. It is expected that two antenna sizes will be required for the multi-arm spiral to accommodate aircraft location limitations. The remaining portion of the RF band could be covered by active phased array apertures which use a large number of monolithic microwave and integrated circuits in the transmitter-receiver modules. Such an approach would use time-multiplexing of the elements of the array to accommodate different frequencies/functions. In addition, areas of array elements across a single aperture can be used to simultaneously perform different functions. Finally a broad band, slotted array may find use in performing signal detection and coarse angle of arrival determination over a large angular coverage will be needed to perform EW receiver functions during time compressed mission phases. A recent PAVE PACE study that investigated the use of these members of a family of apertures concluded that these antennas could be used to cover the entire EW/CNI/radar bands. Thirteen total antennas were required instead of 25-35 unique antennas normally found on today's fighter aircraft.

The direction of RF reception and transmision is controlled by the antenna electronics immediately following the apertures. These electronics are responsible for implementing the aperture's beam forming network and amplifying the received signals. All processing necessary for calculating the aperture's elemental phase and amplitude shifts would be provided by the integrated core processing (ICP). The combined received signals shall be sent to a broadband switch which routs the individual RF signals various frequency converters. These frequency converters are designed to operate over a set frequency band. Their purpose is to up or down convert the RF signals, from or to a common Intermediate Frequency (IF) signals. These are routed to various receivers via an IF switch. This switch is employed to allow flexibility in routing signals of individual frequency bands independent of signal modulation. The signals shall be detected by the receivers. Various receiver types shall be employed depending on the type of signal reception desired. After reception the signal is sent to a preprocessor which converts the signal to zero IF In-phase and Quadrature data. This data is digitized and sent over the Photonic Exchange Network (PEN) to the ICP for further signal processing.

Referring again to Figure 6, only three frequency converters are needed to cover 0.4 GHz to 18.0 GHz. The output of two frequency converters is a single standard IF Frequency (3780 MHz) allowing a common IF switch module to be used to direct the signals to family of common receivers. The third frequency converter is used to accommodate the high dynamic range requirements of radar functions and produces a second, lower IF (2.0 GHz - 2.3 GHZ) to reduce spurious signals. Depending upon the overall aircraft system requirements and concept of operations, a single IF may be used, once again allowing a single IF switch to connect any frequency converter to any receiver module. The output of the IF switch(s) is interconnected to a family of receivers allowing for full interconnectivity between apertures and receivers. To complete the receive process, analog I and Q data is sent to the preprocessors to provide analog to digital conversion, pulse detection, pulse event processing, signal despreading. For transmission, a single multi-function modulator is interconnected to three transmit frequency converters through an IF switch. The frequency converters up-convert the modulated signals and send the signals to the apertures through the RF switch. The aperture electronics provide final amplification and signal transmission. This highly integrated approach to a sensor system can dramatically reduce cost, weight, and volume. For the entire integrated RF design, 120 standard SEM-E modules will be needed as shown in Table 1.

Table 1: ISS Module Types

IF Switch • Transmit - 2 • Receive - 4	RF Switch - 4
Frequency Converters • 0.4 - 2.0 GHz (Receive) - 7 • 2 - 18 GHz (Receive) - 17 • 8 - 12 GHz (Receive) - 4 • 0.4 - 2.0 GHz (Transmit) - 2 • 2 - 18 GHz (Transmit) - 2 • 8 - 12 GHz (Transmit) -2	Pre-processing • Pulse/Nav - 6 • Spread Spectrum - 3 Multifunction Mod. - 3
Receivers • VHF/UHF -5 • IFF/GPS -4 • Multifunction Superhet - 6 • Channelized - 4 • Wideband IFM - 4 • RF Memory - 2	Switch Module - 2 Control Module - 2 Reference Standard - 2 Power Supply - 23

4. Electronic Warfare Concept of Operations Within the Integrated RF System

The PAVE PACE Integrated RF sensor system provides full CNI, EW, and Radar capabilities. With respect to EW, functions can be grouped into three main areas: radar warning with coarse angle of arrival, precision direction finding and electronic countermeasures.
Radar Warning: Figure 7 highlights the resources used to provide radar warning. The following discussions assume an aircraft configuration utilizing two (2) Multi-Arm Spiral Antennas to provide EW capabilities. In this configuration, the MASA's would be connected to the 0.4 - 2.0 GHz converted and 2.0 - 18.0 GHz converter through the RF switch. The signal would be converted to a common IF of 3780 MHz and connected to four (4) Wideband IFM receivers and/or four (4) Channelized receivers depending upon signal densities. Depending upon the given search strategies, the system would systematically cycle through frequencies searching for impinging signals. Due to the fact that MASA antennas provide full spherical coverage (top and bottom with two (2) antennas), search strategies may not require spatial variables. The IFM and/or channelized receiver(s) process the IF signals and send the processed signal to the Pulse/Nav pre-processor which provides A/D conversion and initial processing including pulse detection and pulse event processing. Processed data is then transmitted to a Core Processor for data manipulation.
Precision DF: Figure 8 highlights the resources used to provide precision direction finding. In the same aircraft configuration utilizing two (2) Multi-Arm spiral Antennas to provide EW capabilities, the MASA's would be connected to the 0.4 - 2.0 GHz converter and 2.0 - 18.0 GHz converter using the RF switch. The signal would be converted to a common IF of 3780 MHz and switched to four (4) Multifunction Superheterodyne Receivers to analyze the impinging signal. Like the IFM and/or channelized receiver(s), the Multifunction Superheterodynes are connected to Pulse/Nav preprocessors for initial processing and subsequently to the Core Processor for data manipulation.

Electronic Countermeasures: Figure 9 highlights the resources used to provide electronic countermeasures. Within the integrated RF system, the interconnectivity enables the RF memory receiver, multifunction modulator and transmit converters to provide the desired ECM functions.

5. INTEGRATED RF SYSTEM COMPONENTS

Aperture Electronics: The aperture electronics are located directly behind the MASA antennas and provide the following functions; signal division (triplexers/quadplexers), signal amplification using Low Noise Amplifiers, and signal modeforming. A typical MASA antenna (assuming eight (8) arms), would be "processed" but still provide eight (8) modes to the Rf switch.

RF Switch: The RF switch, located within the RF avionics rack simply provides the interconnect between the aperture electronics and the frequency converters and is constructed in an M x N manner.

0.4 - 2.0 Frequency Converter: The frequency converter receives the signal from the aperture electronics, via the RF Switch, and provides signal upconversion to 3780 MHz. Within the converter, the RF signal is filtered utilizing a band-pass filter and upconverted utilizing a single stage conversion.

2.0 - 18.0 Frequency Converter: The frequency converter receives the signal from the aperture electronics, via the RF Switch, and provides signal conversion to 3780 MHz. Within the converter, the RF signal is filtered utilizing a band-pass filter and converted utilizing a high side conversion for 6 - 14 GHz signals and a low side conversion for 14 - 18 GHz signals. For 2 - 6 GHz signals, the signals are up-converted to 7.5 - 13.5 GHz signals and then downconverted to 3780 MHz.

Wideband IFM Receiver: The Wideband IFM receiver processes a low number of signals and performs very wideband instantaneous RF bandwidth receptions. The IFM obtains pulse-to-pulse frequency information and is usually used to support low density EW search and analysis modes.

Channelized Receiver: The Channelized receiver is used to support high density EW search modes because it is able to simultaneously process numerous signals.

Multifunction Superheterodyne Receiver: The Multifunction Superheterodyne Receiver is used to provide precision direction finding capabilities. This receiver processes single signals and provides high gain signal processing. The input signal is downconverted, filtered, amplified, and processed via a detector/demodulated.

6. ENABLING TECHNOLOGIES

In order to build functionally dense RF circuits which can ve implemented in modular, line replaceable form; two essential infrastructure technologies will be required.

First, monolithic-based microwave circuitry will be essential in order to keep the number of module types and their resulting size to a manageable level. Work is proceeding in several NATO nations to build this type of circuitry.

Second, a reliable, efficient means of packaging and interconnecting these monolithic microcircuits must be available or large, failure-prone circuity will result thereby reducing the potential impact of the ISS design.

An Avionics Directorate contractual effort by Westinghouse Corporation, Baltimore, MD, USA has resulted in a highly attractive RF system packaging approach as shown in figure 10. The unique features of this design include the use of (a), multi-chip packages which contain several RF mircocircuits, (b) a multi-layer motherboard (5"x5") that allows multi-chip module communications and (3) solder-less interconnections (not shown) between the packages and the motherboard. Not only can the size and weight of the RF circuitry be reduced by a factor of 2 - 4 using this approach, but built-in-test circuitry can be added to enable quick maintenance and even in-flight configuration of failed modules.

Work to date on the PAVE PACE program has resulted in a design that shows promise of overcome these hurdles while achieving the above system benefits. Beginning in around 1996, the first building blocks will be ready for testing and by 1998, the ISS system will be available for use as part of an engineering manufacturing development program.

7. INTEGRATED RF SYSTEM COMPARED TO FEDERATED SYSTEMS

Based on the McDonnell Douglas PAVE PACE study, a typical multi-role fighter employing an ISS RF system compares favorably to federated systems based on current R&D technology as shown in Table 2:

Table 2 Comparison of ISS Parameters

	PAVE PACE ISS	Federated Avionics (ICNIA, INEWS, Radar)
Cost	\$3.9M*	\$7.95M*
Weight	500 lbs	1245 lbs
Size	8 cu. ft.	16 cu. ft.
Reliability	225 hrs.	142 hrs.

* 1989 U.S. Dollars.

Table 1 reflects how an ISS system derives significant benefit from both increases in RF micro-circuit and packaging technologies (about 30-35% weight, volume savings), as well as and integration (65-70%). It is assumed that the technology building blocks will be available in 1995-96 and the system demonstrated would occur in 1998.

8. THE FUTURE OF INTEGRATED SENSOR SYSTEMS

Before the beginning of the 21st Century, the authors believes Integrated Sensor Systems can and will be shown to be practicable and highly advantageous. However, the future for its adoption may not be as promising as the technology availability. Integrated Sensor Systems will require significant cultural, organizational and educational "adjustments" to allow for its acceptance. A step-by-step evolutionary approach, eventually leading downstream to the fully integrated system may be the only way to overcome the resistance that is expected.

The authors expects that for retrofit applications, the growing maturity of multi-function RF apertures may lead the way in "forcing" the acceptance of integrated RF sensors, with some form of modular RF, IF and signal processing components being used. It is expected that one (or both) of the following partially integrated RF systems are likely first candidates.

a. Integrated CNI/ESM - functionally integrated RF sensor system (spanning aperture to signal processing) that covers 200MHz to 6GHz and accomplishes both CNI and the lower portion of the threat band for electronic support measurement (ESM). The use of the broad-band multi-arm spiral antenna will be a key driver.

b. Integrated Radar/EC - At a higher (to be determined) frequency band, multi-function radar (e.g. air-air, air-ground, TF/TA, etc) and ESM and jamming functions would be functionally integrated over the complete band. Again, it might be the multi-function aperture which will be a key technology. For this application, very broad-band, multifunction active transmit-receiver modular circuits embedded in the antenna will be time multiplexed to achieve the multi-functionality.

For new aircraft with initial operational capability dates around the 2003-2005 time frame, an entire integrated sensor system is possible for consideration.

9. CHALLENGE TO FUTURE EW SYSTEM DESIGN

Implementation of an ISS system may have more cultural and organizational difficulties than technical. As an integrated system, assets are time shared with functions outside "normal" domains and control over an asset originates from a "remote" decision based on considerations outside one's functional area. In other words, an EW or radar or CNI functional specialist does not "own" an asset, and cannot point to a module and know what function it is performing at a given instant because system software has determined the functional use of that asset. Since the EW community is necessarily made up of specialists who are often deeply focused in a specific area because of the nature of defensive avionics, the issue of how requirements are properly embedded in the resulting integrated design is a serious concern. The EW designer cannot (simply) develop a new system based on self-imposed requirements. EW systems must be responsive to countering enemy assets and therefore is in general, different in design philosophy from radar and CNI equipment. How do these specific requirements and this needed in-depth expertise (ie. knowledge capture) become embedded in the design? How are the voices of dozens of EW specialists heard when the system design is highly integrated and other non-EW specialists are voicing their design requirements? How does the EW community even certify that the design works? Does the ISS design give the EW functional area the proper priority during certain phases of the mission?

How flexible is this design to the constant changes which have to be made in EW both during the design and deployment phases? And, what parts of the ISS design could be used to retrofit existing EW systems? It would appear that the promise or reach of the available technology may exceed our current grasp and that fundamental changes will be required if the benefits of ISS-like designs are to be exploited in the future.

In order to overcome the cultural and specialization barriers across (and sometimes within) EW, radar and CNI, the authors believe that some form of an "Integrated Product Development" (IPD) process implement through an Integrated Product Team (IPT) is mandatory. Quoting from Ref 1, "IPD brings people representing different functions together at the beginning of the development to work as equals in a climate of trust and ownership to imcrementally and simultaneously refine the definition of the total product including its manufacturing, training and support capabilities.

The IPT can be a collection of IPTs organized along the lines of the ISS specification tree. The important features of the IPT however are that: (a) Multi-disciplinary teams are formed throughout the requirements, design, implementation and support phases, (b) IPTs for both managerial and technical areas are formed, possibly blending both government and contractor members equally in numbers and authority in order to create an environment aimed at accomplishment where artificial barriers can be broken down if necessary, (c) A process where minority views can be heard, along with a process for overall concurrence for decisions.

However, the IPT only allows informed decisions to be made in achieving a balanced design after data is made available. Of extreme importance is the need for a set of CAD-based tools that allows the diverse members of the team to simulate the design in detail to ensure their requirements are embodied in the ISS design before hardware and software is developed. Further, such a capability is needed to ensure modifications made later are system-compatible. Design tools are needed to simulate with a high degree of fidelity in order to ensure functional partitioning and time constraints are met, as well as the means through which ISS resource management software is developed and validated. Such an integrated set of tools does not exist and will require development if ISS-like designs are to enter the inventory. However, individual simulation tools do exist at the RF Component and systems levels and will be used during ISS Development.

10. ISS DEVELOPMENT PLANS

In September, 1994, a four year development phase for the ISS will begin under a contract managed by the Avionics Directorate at Wright-Patterson Air Force Base. An IPT drawn from the entire Directorate will be used to help guide the program and to plan future development programs that will hopefully allow subsequent ISS-compatible efforts to be accomplished. The main objective of the program is to demonstrate the feasibility that the ISS architecture supports real time operation of integrated RF operation is practical under stressing mission conditions. The selected contractor team will design the entire system and then develop the critical parts of the architecture that is common to all functions for purpose of demonstration. Several dedicated EW modular assets (e.g. DFRM, DIFM) will be simulated or off-the-shelf hardware will be used.

Lessons learned from this program regarding will be documented and made available for subsequent use.

11. SUMMARY

If acceptable to the avionics sensor community, a functionally integrated RF system would be a significant break-through in the way in which avionic systems are built. Significant cost, weight and volume reduction as well as improvements in availability for RF assets appear to be achievable in comparison with functionally identical systems built using the same componentry but with a federated architecture. The difference results from the benefits of integrating system assets such that resource sharing (time multiplexing) and reconfiguration.

Further, an ISS design would contribute significantly to solving many challenging issues facing avionics. RF assets were seen to be the dominant cost, weight, volume and availability problems on a robust multi-mission fighter. Therefore, the ISS approach provides real hope that avionics costs can be contained and that significantly fewer maintenance personnel and reduced test hardware will result.

Salient features of the ISS design include the use of a small family of standard SEM-E sized modules which implement transmit, receive, RF switching and IF switching functions and a tightly coupled resource manager that schedules and controls the various RF assets depending on crew input, mission phase or information resulting from enemy action or data or information from off-board assets. The switch-based architecture is the key to achieving reconfiguration and hence, a high level of system availability.

Implementing the EW function in a robust manner will likely be the most difficult function due to its inherent nature of covering a huge bandwidth spectrum while simultaneously extracting diverse, short-lived information from dense threats acting in an uncontrolled manner. As a result, several ISS modules types perform only EW functions.

However, several other significant hurdles must be overcome if ISS designs appear on military aircraft. Among these challenges are: IF bandpass diversity needed to avoid interference, overall EMC problems connected with densely packaged circuitry, complexity and size of interface hardware when ISS systems are retrofitted to existing suites of antennas and the complexity of the Resource Manager required to guarantee real-time scheduling and automatic sensor control. Overcoming cultural problems and developing a set of simulation tools that allow EW, radar and CNI requirements to be properly blended into an ISS design that can be shown to meet real-time needs is mandatory.

The next generation ISS is already being investigated so that architecture changes will be minimal when the new technology buliding blocks mature. This new design approach will involve the widespread use of photonics to reduce weight and cost associated with coax circuits and will utilize a much higher use of digital circuitry immediately after The IF section.

References

1. Results of the Aeronautical Systems Division Critical Process Team On Integrated Product Development, Menker, L.J., ASD-TR-90-5014, Nov 1990, Distribution Unlimited

FEDERATED AVIONICS ARCHITECTURE

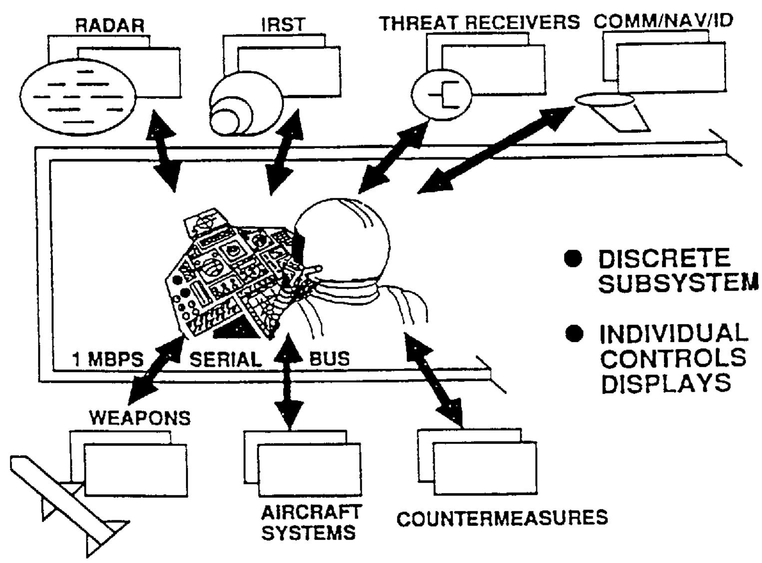

FIGURE 1

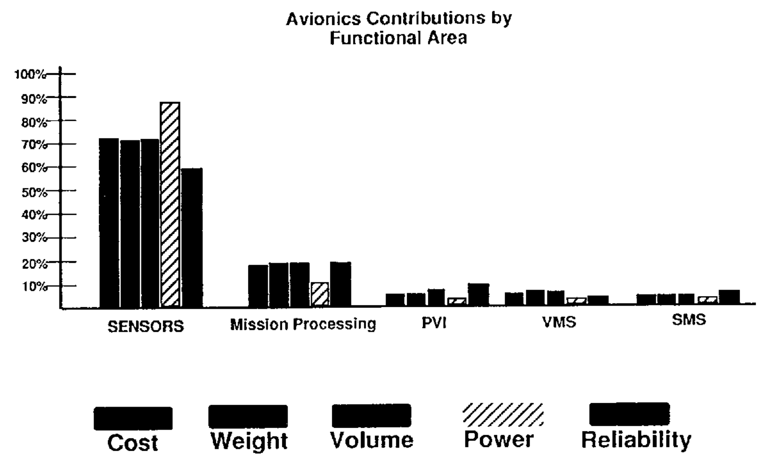

FIGURE 2

INTEGRATED AVIONICS ARCHITECTURE

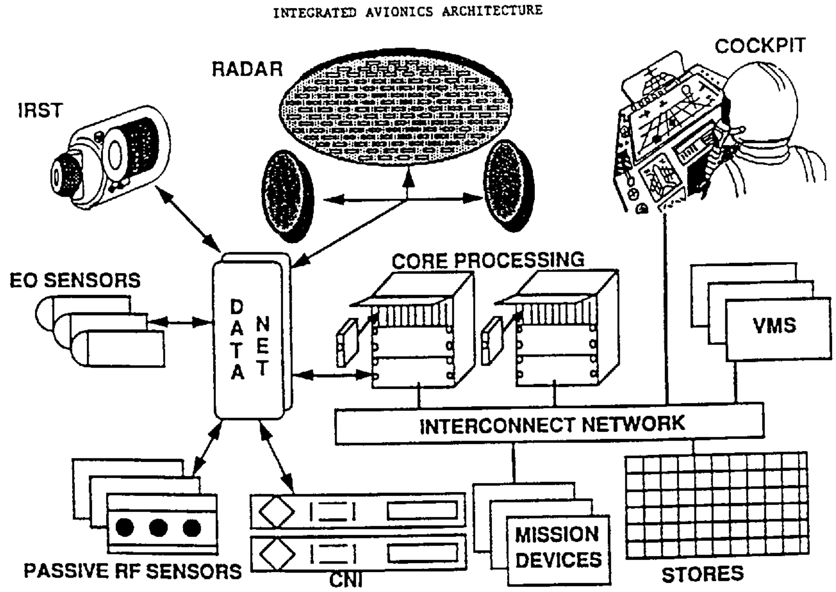

FIGURE 3

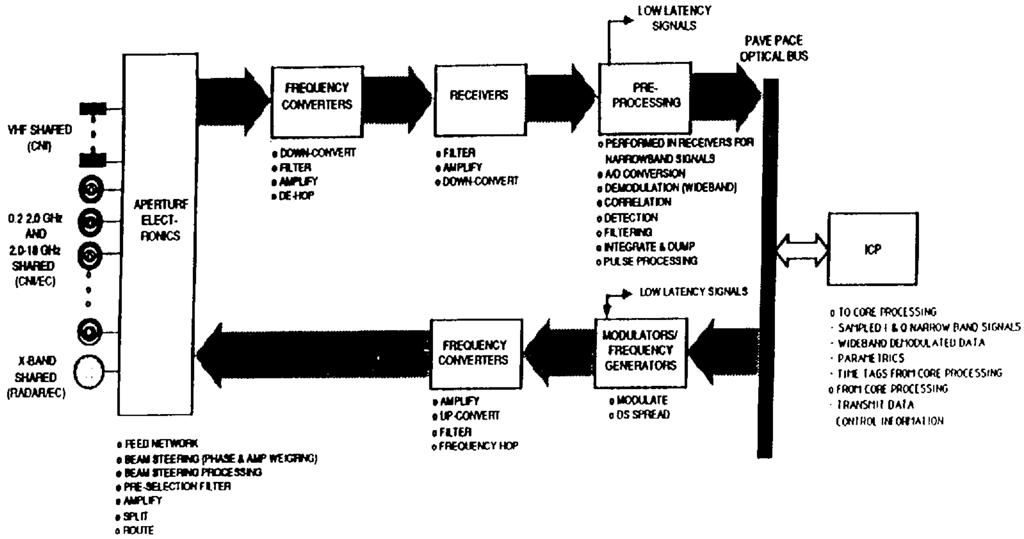

FIGURE 4

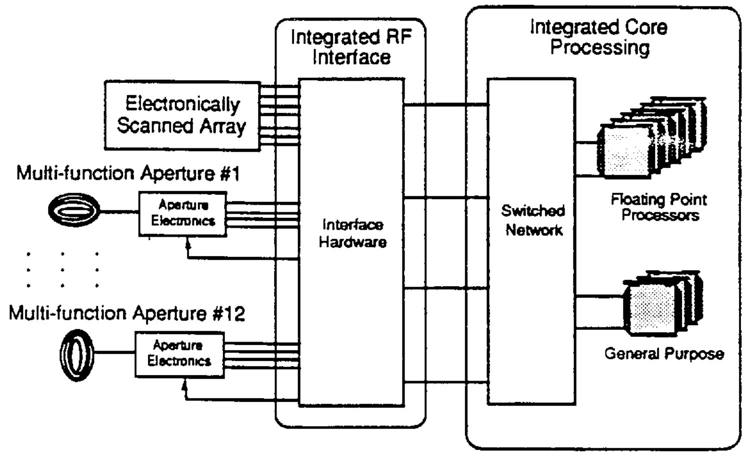

FIGURE 5 Integrated RF Interface

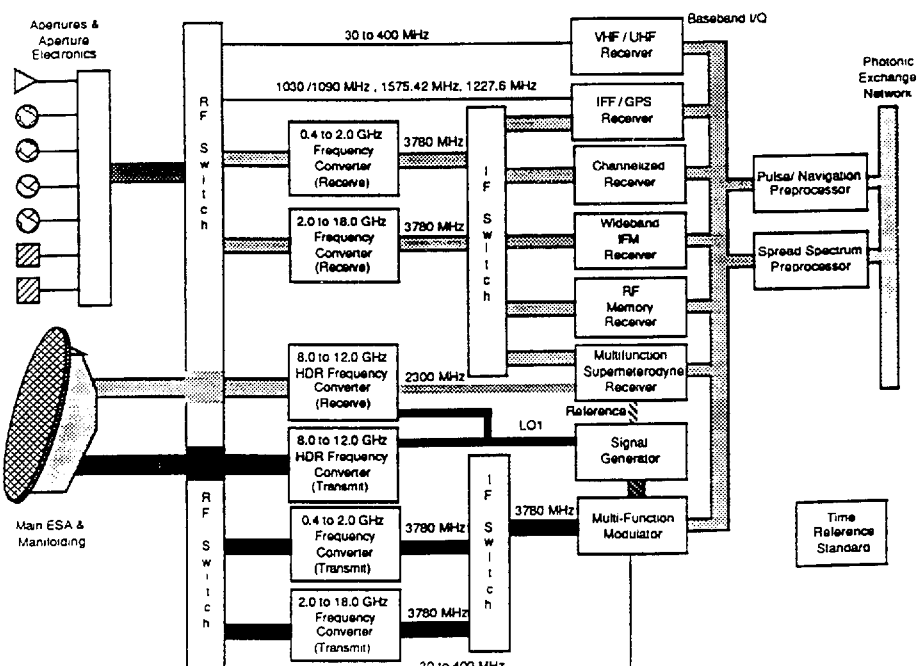

FIGURE 6 Integrated RF System

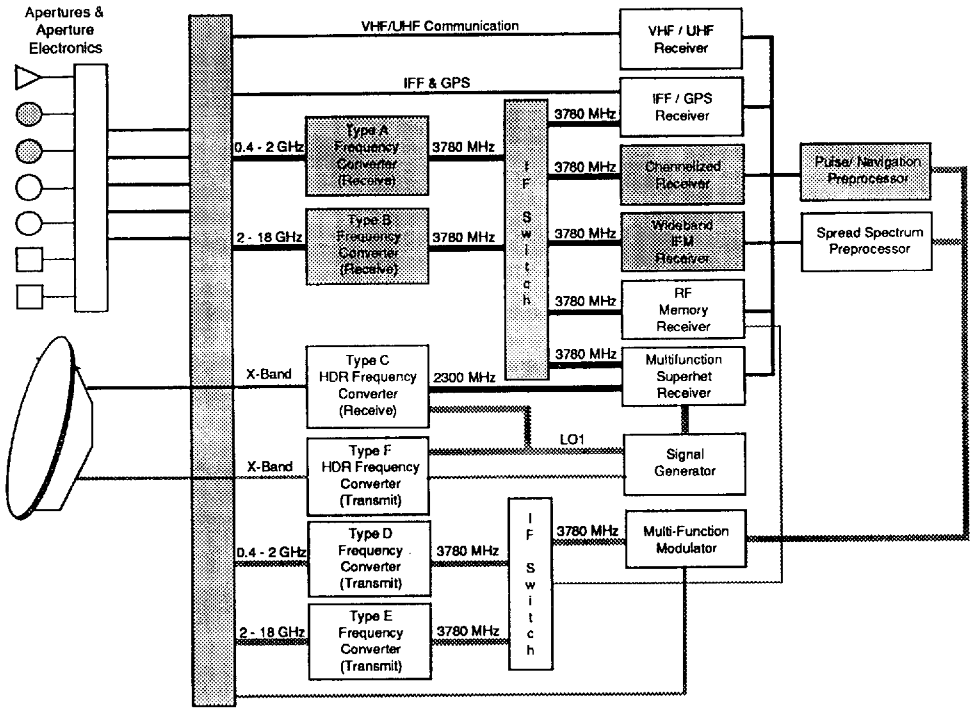

FIGURE 7 ISS RADAR WARNING MODE

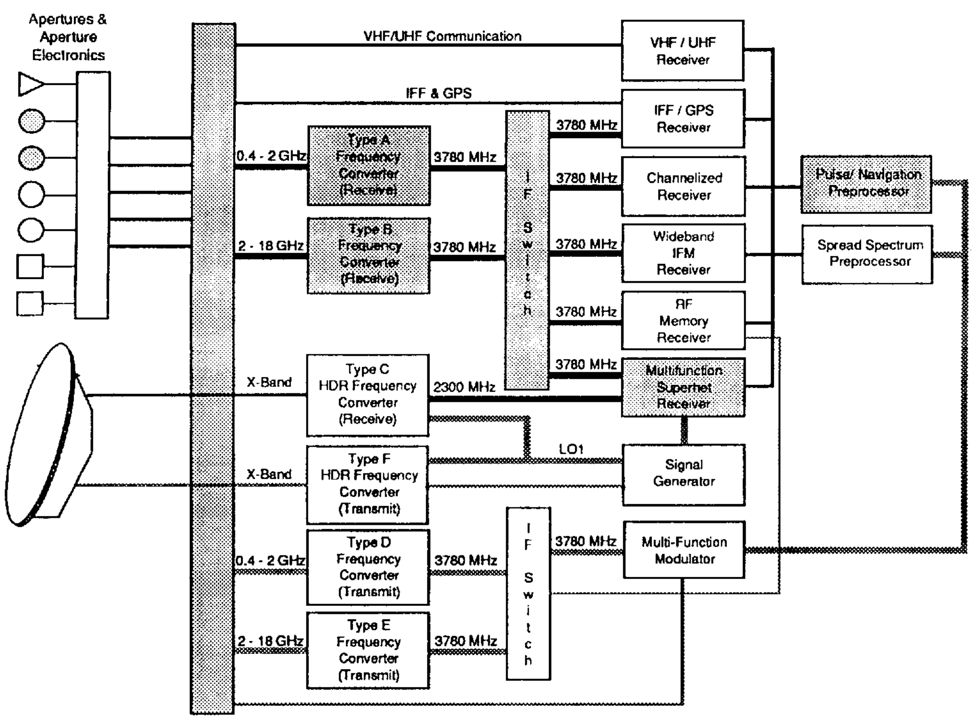

FIGURE 8 ISS PRECISION DF MODE

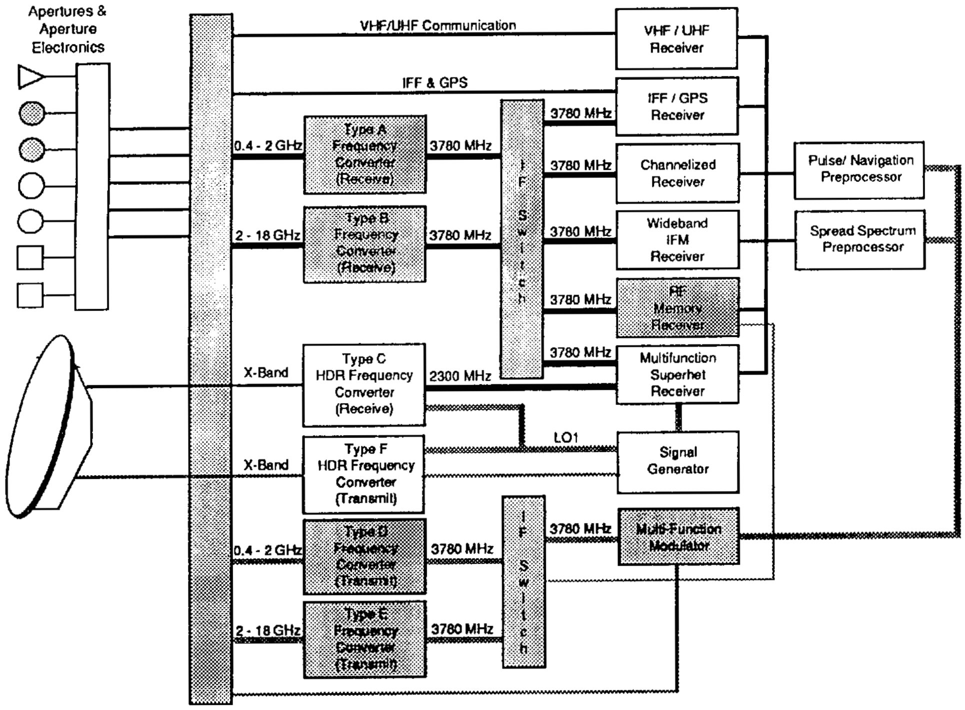

FIGURE 9 ISS ECM MODE

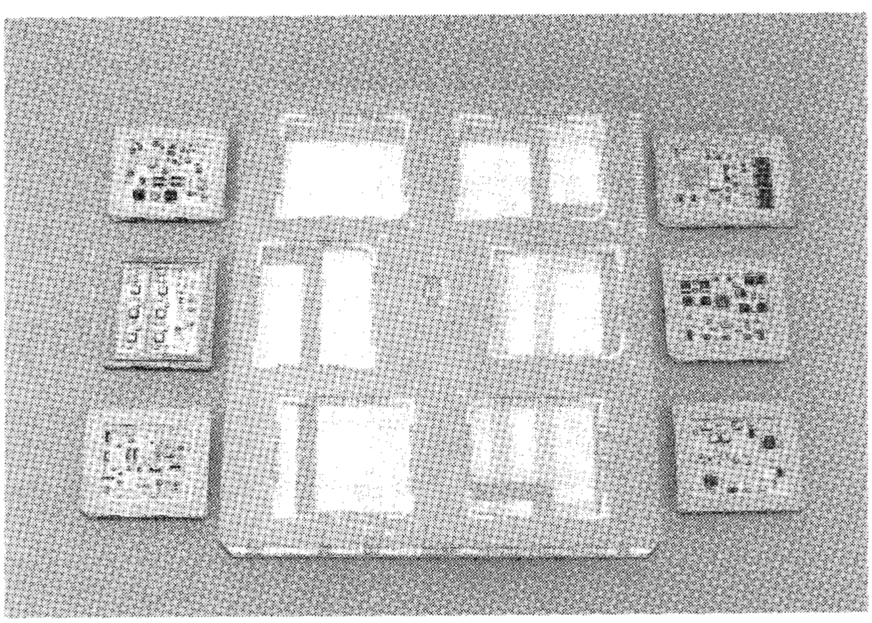

FIGURE 10

Discussion

1st DISCUSSOR : **M. M. DEZANY (UK)**

Does the integrated RF sensor system offer increased availability, similar to the core processing area, through reconfiguration and resource pool techniques ?

Author's reply : yes !

2nd DISCUSSOR : **M. C. HINDS (UK)**

How do you reconcile the sharing of a single asset such as the phased-array antenna area high duty-cycle functions without unacceptable degradation in performance ?

Author's reply :

The current design assumes the ESA aperture will be used for fine AOA ESM after other EW/ECM antennas have been involved in localizing threat positions. After handoff to the ESA for selected threats, the integrated sensor resource manager shares the ESM job with radar functions. As the fine AOA ESM work load increases, Air-Air radar modes are cut back and then dropped (if necessary) for, say, a low-level penetration mission-phase, radar load shedding continues based on priorities, with the ground map mode being shed. Finally, the radar is doing only the terrain Following/Avoidance radar function with ESM/ECM taking up the rest of time.

The question now becomes on of determining if the ground or the threat poses the greatest danger in allocating the resources.

I am sure we could postulate a threat scenario so dense that full time use of the ESA for EW assets would be required.

In the next phase of our program, we will be addressing these issues for the scenarios assumed so far, there hasn't been a "problem".

If there is, here are, some "fall-back" modes :

- placement of dedicated forward-looking ESM quality antenna on aircraft (possibly on the ESA antenna),
- use of stored terrain datas to permit minimal use of radar in terrain following mode, thereby giving the ESM/ECM function a much larger duty-cycle plus increased stealth (the radar TF/TA mode only looks a short distance in front of the aircraft). We, also, will be changing flight-paths to use the terrain to mark the threat(s). There are, however dedicated RWR antennas (around 10 degrees AOA accuracy) for use on a 100 % duty-cycle. I hope this helps. Your question is a very good one, and more work is required to answer it with complete confidence, the whole issue of the "shareability" of RF assets in dense signal environments is the real issue of fonctionnally integrated RF systems.

ADAPTIVE MISSION PLANNING[1]

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J. Mark Reynolds
Robert E. Collins
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Attack Weapons Department
Naval Air Warfare Center Weapons Division,
China Lake, California 93555-6001, U.S.A.

SUMMARY

This paper discusses the need, the components, and the implementation of an adaptive mission planning system. In order to be successful on today's complex battlefield, one must be able to adapt in real time to the dynamic environment. The capability must exist to automatically replan missions while *en route* to the target areas.

The main components of the adaptive mission planning system are the controller, the route planner, and the strike planner. Each subsystem is discussed in terms of its function and its implementation. The final section is a description of an approach for simulating the adaptive mission planner using an m-on-n simulation.

INTRODUCTION: AN ADAPTIVE STRIKE PLANNER

Mission planning has become more complex over the years. At one time a mission plan could be created and used later. Today, changes on a battlefield can occur rapidly, and the effects of these changes could lead a strike into disaster. The Mission Planner must be able to create new plans as the previous mission plan is conducted, and the mission plan must be able to change quickly as new and vital information is gathered. Also, components of the plan must have autonomous decision making capabilities.

Modern combat evolves rapidly, with transportable threats such as the highly movable SA-15 causing threats to appear where there were none previously. Targets may be destroyed before the flight arrives on the scene by another attack group or by other members of the Strike Group. Members of the Strike Group, whether manned aircraft or cruise missiles, represent costly national assets. They warrant the highest degree of protection, within reason, to ensure that the mission is completed.

The way that the mission plan is changed must be controlled, reliable, and predictable, given knowledge of the initial database. The flight path must not go into mission restricted areas nor attack non-targets. The time of the mission must also be controlled in order to minimize the risk of interfering with the next attack flight or major attack thrust. The use of force must be controlled and restricted, with reduced collateral damage and minimal danger to noncombatants. Only the hostile war fighting capability must be destroyed.

At present, the plans do not optimize the mission for one air vehicle but rather for the entire Strike Group. As recent history has shown, the North Atlantic Treaty Organization (NATO) does not send only one missile into conventional combat at a time or only one manned aircraft. NATO sends a strike force. The problem is that the optimal Strike Group plan is rarely the summation of optimal mission plans of each individual aircraft.

In order to keep up with the changes, the mission of the strike should be updated *en route*. The mission of the strike force must reflect the most current circumstances related to the battlefield.

OVERALL ARCHITECTURE

The architecture of this adaptive strike planner must contain several intelligent components. The controlling power will reside within the Fuzzy Logic Expert System (FLES) controlling the action of other components, with the database as the memory of the controlling power. The Route Planner gives options to the overall system, and the Strike Planner picks the optimal option.

[1]Task title on which this paper is based: Air Weaponry Technology Program (AC1A), no. 13-1(RU11S22); Adaptive Mission Control subtasks 13-1.1, Expert System Architecture; and 13-1.2, Adaptive Strike Planner.

Presented at an AGARD Meeting on 'Challenge of Future EW System Design', October, 1993.

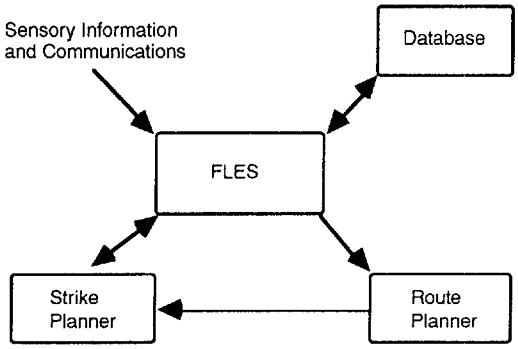


FIGURE 1. Schematic of the adaptive strike planner.

FUZZY LOGIC EXPERT SYSTEM

The fuzzy approach combines the purely numerical approaches of mathematical modeling with the symbolic, structure-rich approaches to decision making. We acquire the knowledge symbolically (poor, fair, good), but represent this knowledge numerically. Adaptive Fuzzy Associative Memories (FAMs) rules[2] correspond to common sense rules that improve with experience.

The Fuzzy Logic decision making tools were selected because of the uncertainty of the information handed off the missile/aircraft system. Besides the information handed off, there are degrees of confidence[3] for each portion of the information. For example there may be categories for a target no. 1 destroyed (D) and no. 2 targetable (T). If a target has been struck and it appears to have 75% damage, then the target may be placed in the destroyed category with a value of 0.75 and into the targetable category with a value of 0.25. Thus it is not a question of whether the target has been struck, but rather of how well. The same target is actually in two separate categories: "destroyed" and "targetable." Like Schrödinger's cat[4], we have one target with seemingly two realities. If we state that $U = D \cup T$ and $D \cap T = \varnothing$ then the target is either destroyed or not. We would have to describe our target as destroyed or targetable. The problem is, which one? At what point of damage does a target become destroyed?

[2]Kosko, 1992.

[3]Not the statistical definition of confidence.

[4]I am referring to the famous cat in the box with a poison that has either killed the cat or has left the cat alive. Schrödinger postulated that in our reality there are two cats, one dead and one alive. Only when we make an observation are the answers revealed. The difference in Schrödinger's cat is that the poison is turned on (or not) by a quantum mechanical system. In destroying the target (or not), there is no quantum mechanical system directly involved. Much of the "fuzziness" associated with target destruction is, in part, due to a definition problem and not to a fundamental feature of nature.

The set we are working with is fuzzy, i.e., the classification is not clearly defined. Is a target destroyed when the damage to the target reaches the 75% level? Then what if the target is only 74.5% damaged? Can the criterion be changed? Figure 2 graphically displays the problem.

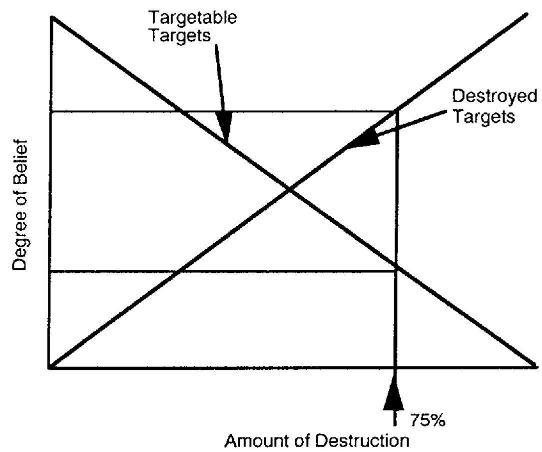


FIGURE 2. Fuzzy data can exist in two conflicting sets.

The next question is whether to strike the target again. More information is needed, and an evaluation must be performed. The evaluation is done with Fuzzy Logic.

The rule set is developed by personnel who are considered experts in the field of targeting. After the rule set is developed, the FLES can act independently of human input. The system may be designed for human intervention and approval, however it is not necessary.

As an example, if Battle Damage Assessment (BDA) could indicate that:

1. If target ID (identification) is good and BDA is low, then attack the target
2. If target ID is good and BDA is high, then do not attack the target
3. If target ID is poor and BDA is low, then do not attack the target
4. If target ID is poor or BDA is high, then do not attack the target

then for this example only, the matrix of values[5] shown in Figure 3 may be derived:

		Target ID	
		Poor	Good
BDA	Low	Do not	Attack
	High	Do not	Do not

FIGURE 3. Rule matrix for the example.

[5]This is an example only.

The problem with this concept is that most data cannot fit easily into low or high categories. For example, if the target ID assessment gives a confidence of 0.65, then is the target ID Poor or Good? Figure 4 is a pictorial of this problem.

According to this graph it is more believable that 0.65 confidence is Good; however it could be Poor. A similar graph could be produced for the BDA, so how can we infer the solution for the logic matrix?

Performing an inference is the process of applying the degree of membership computed for a production rule premise to the rule's conclusion. This determines the actions to be performed. In our work we limit ourselves to two inference methods: max-min and max-dot. In either inference method, the basic concept is that the value (set) to be assigned to the output is scaled by or clipped to the degree of membership for the premise. Therefore we must treat all the scaled or clipped sets for all the rules that set this output to form the final output membership function. The two methods give very similar results.

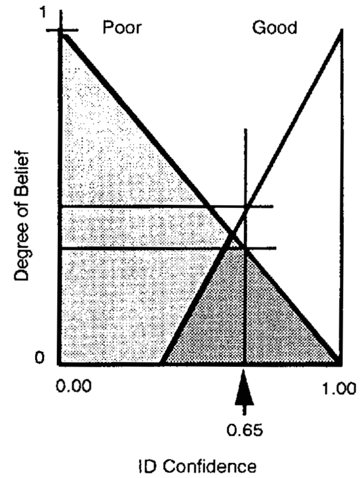


FIGURE 4. Is a target ID Good or Poor?

In the max-min inference method, the final output membership function for each output is the union of the fuzzy sets assigned to that output in a conclusion after clipping their degree of membership values at the degree of membership for the corresponding premise. Figures 5 and 6 illustrate both methods.

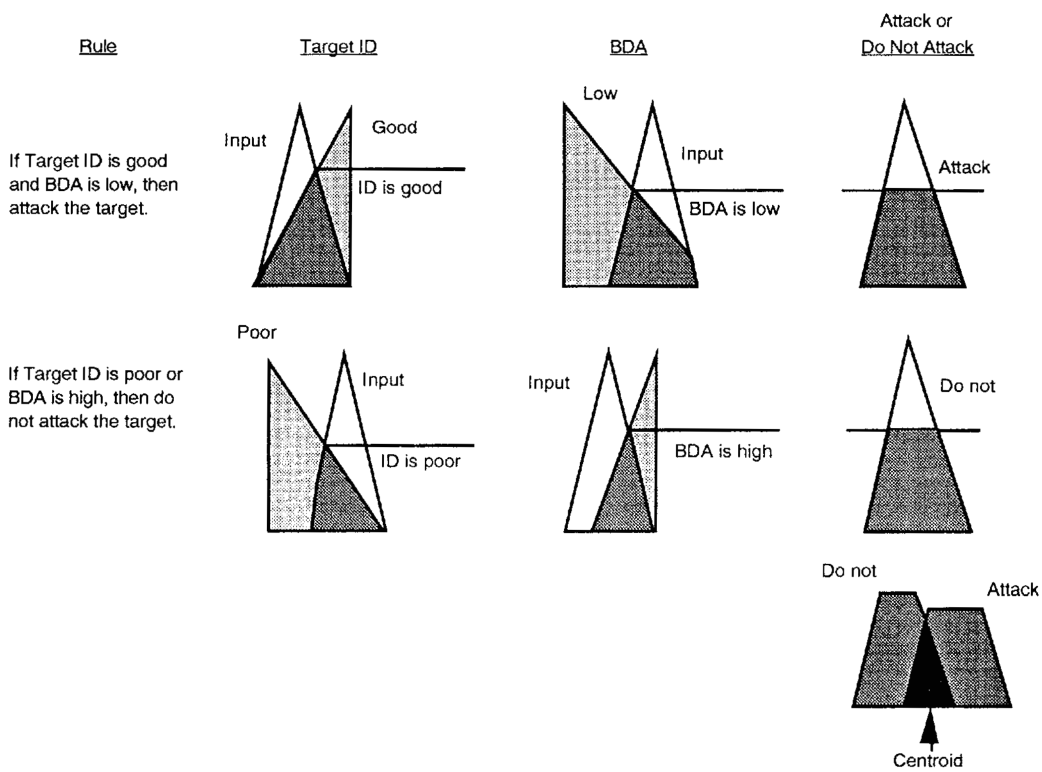


FIGURE 5. The max-min inference method.

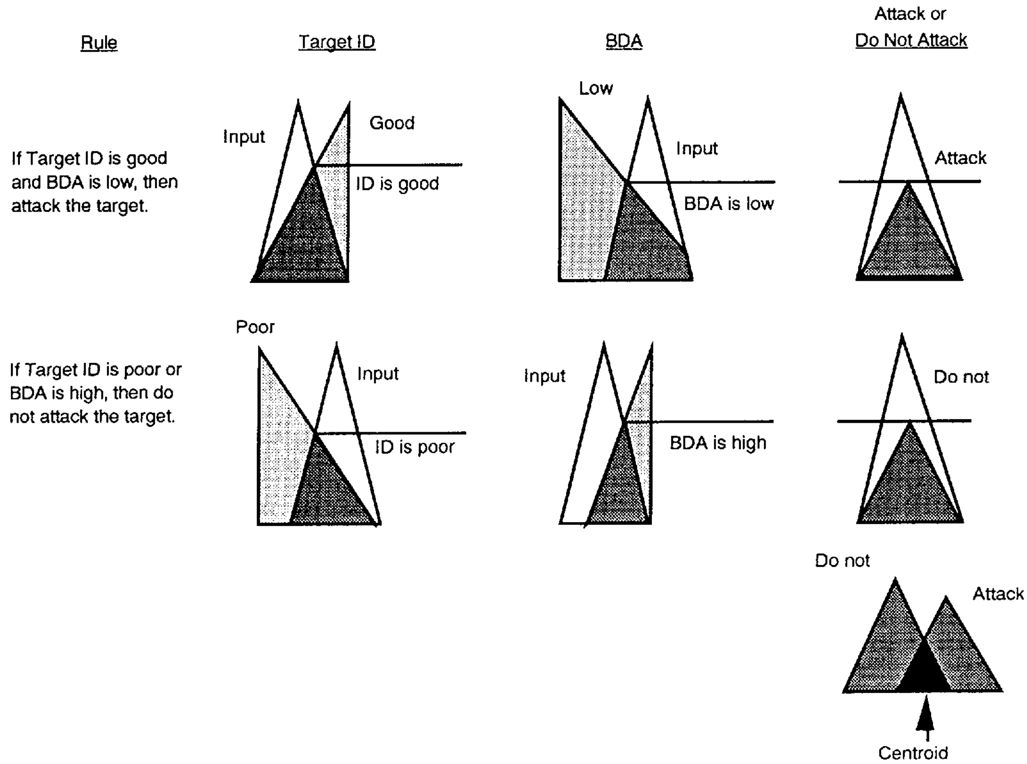


FIGURE 6. The max-dot inference method.

The "and" logic operator chooses the minimum of the rule set and the "or" logic operator chooses the maximum of the rule set. For determination of the results, all the rule sets act toward and aid in the final decision. In this pictorial, only two of the rule sets were used.

The result of either method is the same.

The results of fuzzy logic inference are fuzzy values. However in this project, there is a need for a crisp binary answer: Attack - Do Not Attack, Replan - Do Not Replan, Communicate - Do Not Communicate, Self Destruct - Do Not Self Destruct.

The centroid defuzzification method picks the output value corresponding to the centroid of the output membership function as the crisp value for an output.

DATABASE

The database must contain the following: terrain information, vertical obstruction, target type, target location, target value, target damage indicator, threat location, threat type, threat lethal area, no-fly zones, important-fly zones, duration of mission, flight constraints of the platform, and information on all the other strike platforms.

ROUTE PLANNER

The Route Planner uses the optimization routine of Dijkstra's algorithm.

The concept is to find the shortest path in a graph. We are given a cost, directional graph G = (V,P), with cost function $c: E \rightarrow R$ mapping paths to real valued costs. The cost of path $p = (v_0, v_1, ..., v_k)$ is the sum of the costs of its constituent paths:

$$c(p) = \sum_{i-1}^{k} c\left(v_{i-1}, v_i\right)$$

We define the shortest path cost from u to v by

$$\delta(u,v) = \begin{cases} \min\{c(p) : u \overset{p}{\rightarrow} v\} & \text{if a path exits} \\ \infty & \text{otherwise} \end{cases}$$

A shortest path from vertex u to vertex v is then defined as any path p with cost $c(p)= \delta(u,v)$.

Dijkstra's algorithm solves the single-source shortest-path problem on a weighted, directed graph G = (V,P) for the case in which all path (P) weights are non-negative and all vertices (V) are positions on the computer version of the map.

Dijkstra's algorithm maintains a set S of vertices whose final shortest path weights from the source s have already been determined. That is, for all vertices $v \in S$ we have $d[v] = \delta(s,v)$. The algorithm repeatedly selects the vertex $u \in V - S$ with the minimum shortest-path estimate; inserts u into S; and relaxes all edges, leaving u.

As an example, $s \in S$ and $u, v, x, y \in V$ initially.

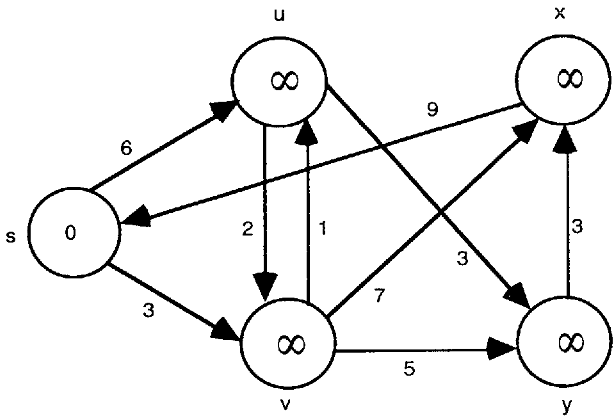


FIGURE 7. The source is labeled s and the value assigned to the rest of V is given the value ∞.

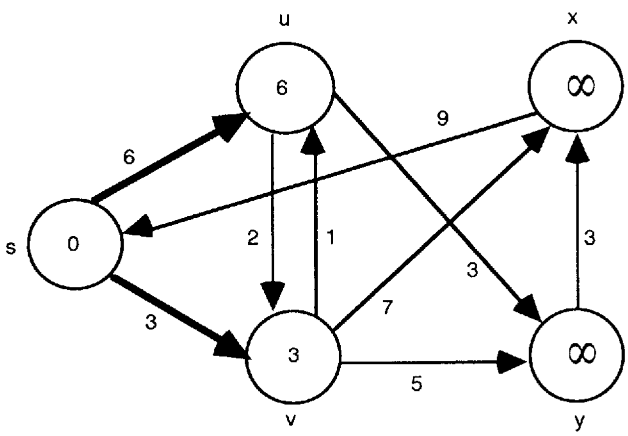


FIGURE 8. The path (s,u) is now relaxed to the value 6 and the path (s,v) is relaxed to the value 3.

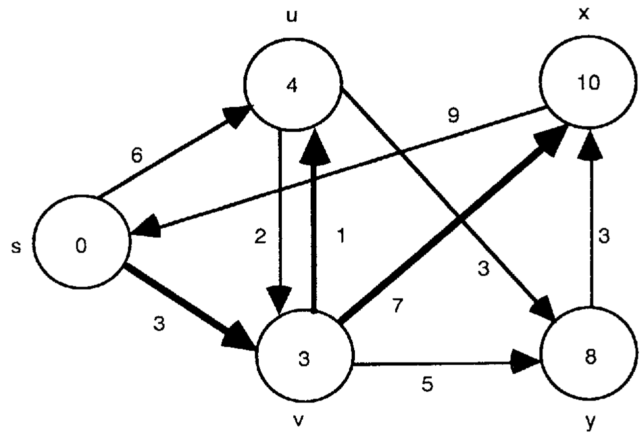


FIGURE 9. Now the path (s,u) is found to be more expensive than the combination of paths (s,v) and (v,u), so the value of u (6) is replaced by the new value 4 (3 + 1). Also the value is relaxed for x and for y. The vertices s, v, and u are now in S and the vertices x and y are still in Q = V - S.

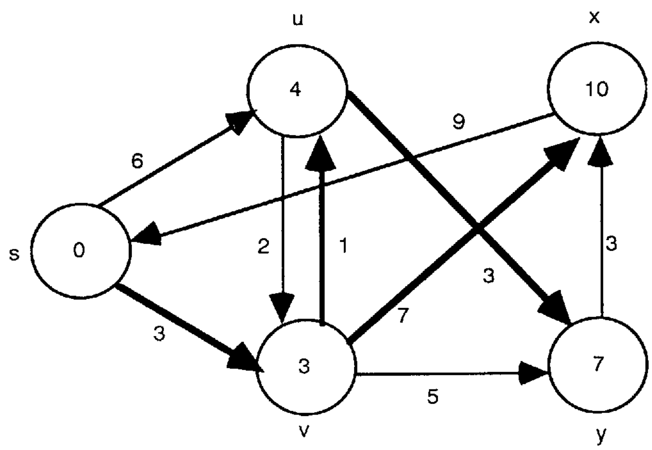


FIGURE 10. The solution from s to v, u, x, and y has been found.

The algorithm for this procedure is:

Dijkstra

```
Initialize - Singe - Source
S ← ∅
Q ← V[G]
while Q ≠ ∅
     do u ← Extract - Min. (Q)
     S ← S ∪ {u}
          for each vertex v ∈ adj[u]
               do Relax (u, v, w)
```

The computer algorithm (Wavefront)[6] adds several other features. One of the features is that the algorithm is constrained to no more than a $\pi/4$ radian turn. This aids in constraining the software to produce only physically possible turns given a particular air frame. For more detail see the section, "Cost Matrix."

The algorithm must be performed so that each missile will have an optimal route (least cost) to each possible target. For each missile location (s), target location (t) will be considered separately. The missile location is s and we find $d[v] = \delta(s,t)$ with the path to each target.

This information (path and cost of each missile to each target) is passed to the Strike Planner.

STRIKE PLANNER
The Strike Planner uses the cost of each route calculated by the Route Planner for each missile to each possible target. The minimal cost of the strike is then calculated by using a variation of the assignment problem, with special considerations. Total supply does not equal total demand. Rarely will the number of missiles available equal the number of missiles needed to serve all the targets.

Implementation of the strike planner involves the use of a Hopfield Feedback Neural Network.[7] A Hopfield Net consists of an array of neurons implemented as nonlinear thresholding amplifiers, with a sigmoidal transfer function, fully interconnected via synapses of programmable strength.

[6]Developed by Jeff Sulka at NSWC Dahlgren.

[7]Neural Network developed by Dr. Taher Daud and Dr. Anil Thakoor at the Center for Space Microelectronics Technology, Jet Propulsion Laboratory.

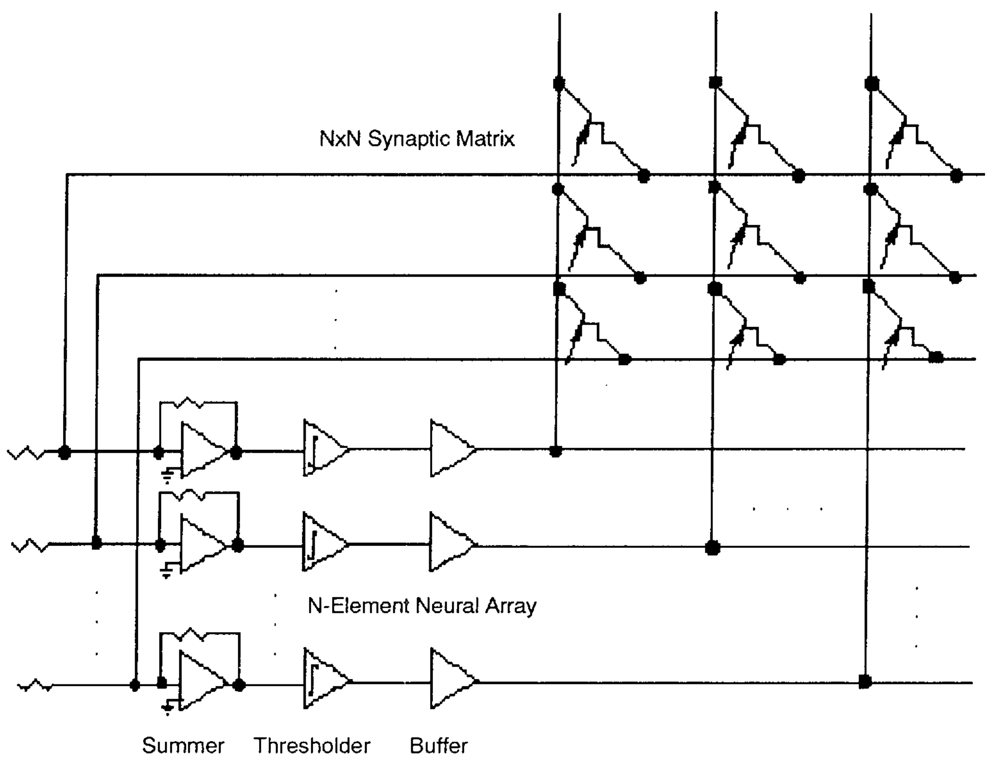


FIGURE 11. Schematic of a Hopfield Feedback Neural Network.

THE COST MATRIX

The Cost Matrix, as well as the information matrices, is formed by overlaying grids on a map of the region in question. The grid cell sizes as related to the map are proportional in the x, y, and z axes for the flight characteristics of the flight platform. We assume that the flight platform can only accomplish a maximum of π/4 radian turn within a grid cell; therefore, if a flight platform can perform a 2 π radian turn in a 2-kilometer-diameter circle, then each grid cell must measure 0.63 kilometer per side.

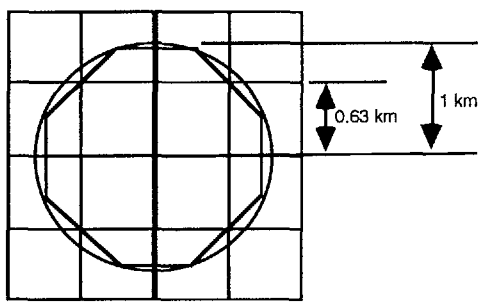


FIGURE 12. Grid size drawing.

The computer program assumes that the flight platform will go to the center of each grid cell, so the circumscribed straight lines represent the computer model of the turning path that is represented by the circle. Each of the line segments of the circumscribed straight lines also have the maximum turn of π/4 radian for each grid cell. Notice that 1.5 grids (g) covers a linear distance of approximately 1 kilometer, so we use 0.63 kilometer as the distance along the side of the grid cell.[8]

Each grid cell will be given a value for the probability of:

- Hitting the ground (terrain)
- Hitting an obstacle (vertical obstruction)
- The possibility of being shot down via anti-air guns or surface-to-air missiles (threat)
- How much fuel will be consumed by crossing the grid cell (fuel expenditure)
- The ideal path to approach each target (weaponeering considerations)
- Zones that we prefer not to fly through or that we wish to fly through for political or humanitarian reasons (no-fly and important-fly zones)

[8]Appendix 1 gives the mathematical derivation.

Each of these considerations will constitute an information matrix. Each of these information matrices will be held in memory by the database. For each grid cell there will be one set of matrices containing all the information previously mentioned. An example of a possible grid cell arrangement is given in Figure 13.

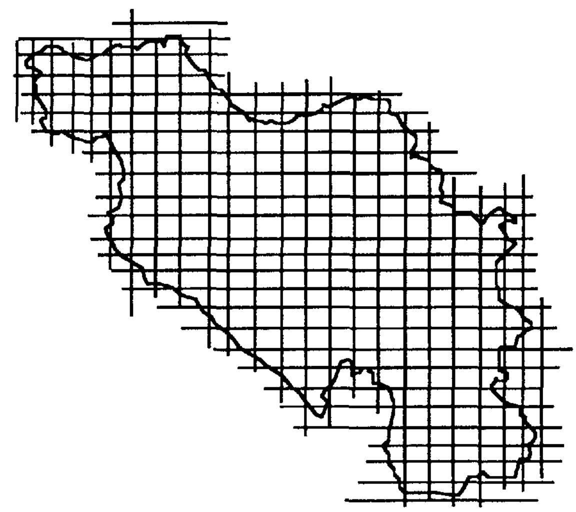


FIGURE 13. Grid cells superimposed over a land mass.

The final Cost Matrix is a weighted sum of the information matrices

$$C = \sum_i w_i M_i$$

where C = the Cost Matrix
M = the individual information Matrix
w = the weight for the Matrix as assigned by FLES
i = the index for the information Matrix and weight

The weights are determined by FLES as appropriate for the current state of the mission.

PROGRESS TASK

Currently we have developed a method to obtain information from and place new information into a many-on-many computer simulation.

The Route Planner is being developed by the Naval Surface Warfare Center, Dahlgren, Va.

The Strike Planner is being developed by the Jet Propulsion Laboratory (JPL) associated with the National Aeronautics and Space Administration (NASA) and the California Institute of Technology (CALTECH).

China Lake is developing the FLES and database.

CURRENT DEVELOPMENT

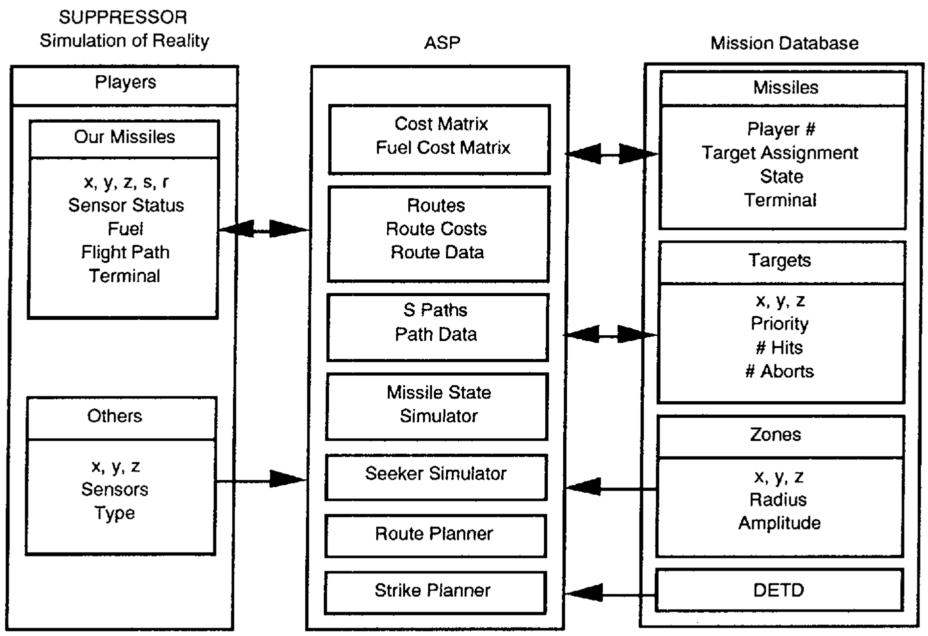


FIGURE 14. Current development.

The source of information derived from the computer software will change when the Automatic Strike Planner moves to an actual missile. The software has been written so that the change from SUPPRESSOR to actual sensors and communications will not create undue problems.

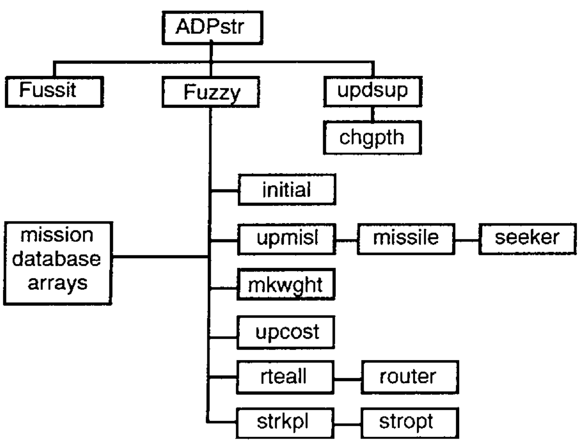


FIGURE 15. Adaptive strike planner block diagram.

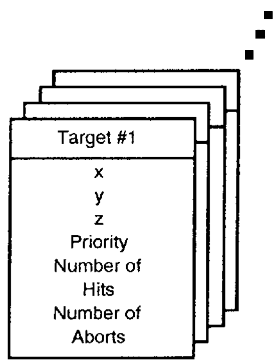


FIGURE 16. Target database.

This list is to be read from an input file and is to represent a portion of the mission database. Upon initialization (subroutine named initial), an input file that represents pre-launch mission planning will be read into the mission database. The number of hits and aborts will be set to zero. As the scenario continues, the subroutine "upmisl" will update the number of hits a target receives and also the number of times a missile aborts this particular target. An aborted mission means that the seeker onboard the missile could not recognize the object in its field of view as a target. Not recognizing a target may happen in several ways:

- Adverse (or worse) weather.
- Missile/seeker malfunction.

- The target is damaged to the point that the seeker's identification routine could not tell that it was the target.
- The missile is off course to the point that the object in its seeker field of view was not the actual target.

If the missile is off target, then the missile should recognize this fact and use FLES to decide to reapproach the target from a different angle.

The Strike Planner uses a function of Priority (the priority that the human mission planner gave a particular target), then number of hits (each hit reduces the target's targetability level), and the number of aborts (an indicator of the target's damage level) to produce the internal priority for each target.

A target is never completely destroyed as far as the computer program is concerned. The Route Planner always plans routes from each missile to each target.[9] The Strike Planner can ignore targets that have a low internal priority level.

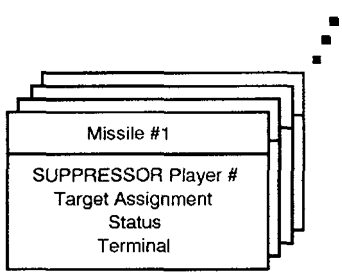


FIGURE 17. Missile database.

This list is to be read from an input file and is to represent a portion of the mission database. Upon initialization (subroutine named initial), an input file that represents pre-launch mission planning will be read into the mission database. The data contained include:

The SUPPRESSOR Player number is used in the development stage of the program; later it will become a mission identification number.

Target Assignment is the target that the missile is to attack.

Status numbers are indices that describe the current missile status:

0 - Dead: Destroyed by threat action.
1 - Cruise: The missile is *en route* to a target.
2 - Commit: The missile is attacking a particular target (the target given in Target Assignment).
3 - Abort: The missile could not find the correct target with sufficient confidence, or the BDA of the target indicates that the target has been destroyed (this relates to an abort).
4 - Impact: The missile has impacted the target (this relates to a hit).
5 - Terminal: The missile is in a terminal attack on the target (the stage of the missile flight in which nothing will interfere with its flight).

The subroutine "upmisl" will update the information in the missile list as the scenario progresses.

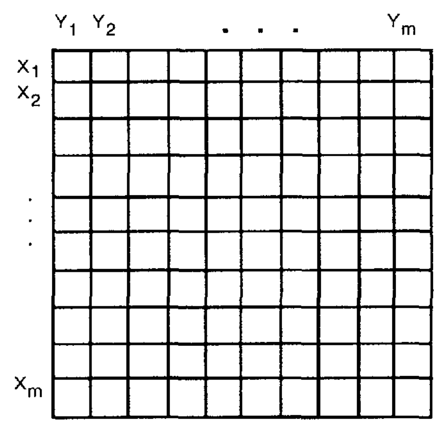


FIGURE 18. Cost matrix.

The Cost Matrix combines terrain, vertical obstructions, threats, weaponeering considerations, and no-fly and important-fly zones into one matrix and the fuel expenditure into another matrix. Terrain, vertical obstruction, threat, weaponeering considerations, and fly zones all cause the missile system to be routed in such a way that would burn more fuel. The major change expected as the scenario runs will be the amount of fuel left onboard the missile.[10]

The weighting factors of the Cost Matrix and the Fuel Matrix will be different for each missile. The amount of fuel left in each missile will be considered individually by Fuzzy Logic. The weight of the Fuel Matrix will increase as the amount of fuel decreases.

As was stated in the Cost Matrix portion of this document, each grid cell represents a particular area of land mass. Each grid cell must be correlated to the game

[9] This method may be changed in more advanced versions of the program to save run time.

[10] This method will change when a more advanced version of the program is produced in order to examine effects of additional information. As yet, it has not been determined that a significant improvement in missile performance can be achieved by examining the trade-offs for all components.

area in SUPPRESSOR. One method of restricting the flight to the game area is simply to make the cost of any grid cell outside of the game area equal to ∞.

The Route Planner will develop a matrix of missiles and targets. Each combination of missile and target will be analyzed and the resulting Way Points will be loaded into a data array. There will also be an array that contains all of the costs for each missile/target combination.

Only missiles that are not dead (impact or dead) will be used; therefore as the scenario runs, the size of the array will decrease.

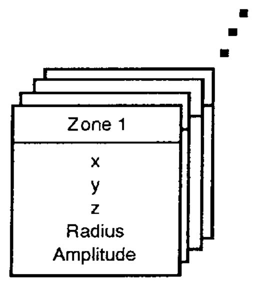


FIGURE 20. Fly-zone database.

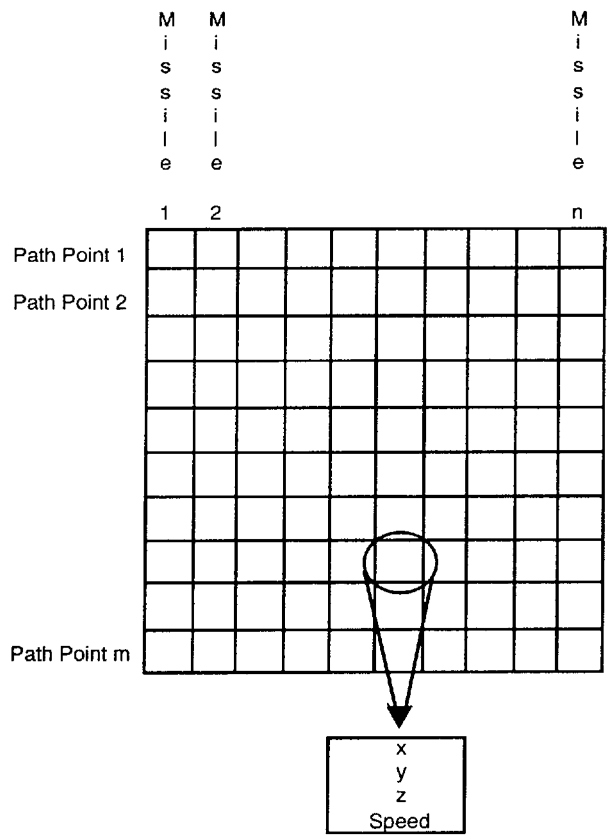


FIGURE 21. Optimal route matrix.

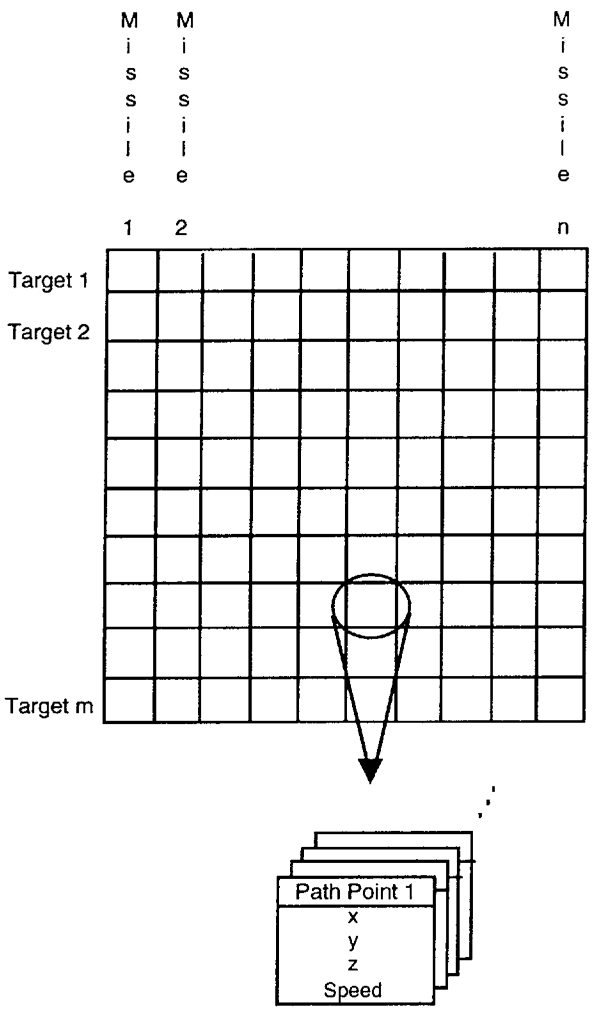


FIGURE 19. Master route matrix.

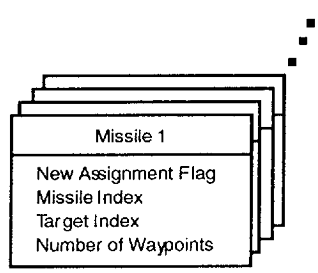


FIGURE 22. Optimal route data.

Upon initialization (subroutine named "initial") an input file that represents pre-launch mission planning will be read into the mission database. This information represents no-fly and important-fly zones. No-fly zones will have a positive cost (amplitude) and important-fly zones will have a negative cost. To simplify the problem, Weaponeering Aspects will be a portion of the Fly Zones.

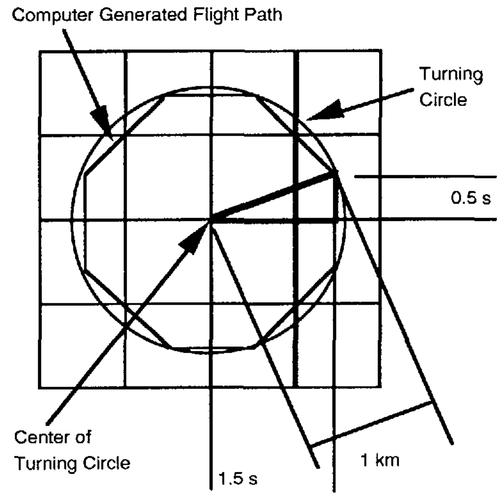
This array is filled with the waypoints that the Strike Planner picks from the choices that the Route Planner makes available. This array has only one route per missile, containing the x, y, and z axes along with the speed for each waypoint. This is the information that is passed back to SUPPRESSOR.

CONCLUSION

The battlefield of tomorrow will require real time, adaptive mission planning. Missions will have to be replanned while they are in progress. We have looked at the implementation issues for the controller, the route planner, and the strike planner. These subsystems are then integrated together to form a viable adaptive strike planner.

APPENDIX 1

The computer program assumes that the flight path will go through the center of each grid. Thus the path of a turning airframe will pass through a point that is 1.5 s and 0.5 s from the center of the turning circle (see the drawing below). This produces a nice right triangle for us to use.



$$(1.5\ s)^2 + (0.5\ s)^2 = 1.0$$
$$2.25\ s^2 + 0.25\ s^2 = 1.0$$
$$2.5\ s^2 = 1.0$$
$$s^2 = 0.4$$
$$s = 0.6324\bar{5}$$

REFERENCE

Bart Kosko. *Neural Networks and Fuzzy Systems; A Dynamical System Approach to Machine Intelligence.* Englewood Cliffs, N.J., Prentice-Hall, Inc., 1992.

Discussion

1st DISCUSSOR : **M. S. YARMAN (TU)**

How do you guarantee the convergence of the process ?

Author's reply :

Missiles path optimization field is different than the aerial net optimization field.

2nd DISCUSSOR : **M. MULTEDO (FR)**

Can you give us more explanations on the cost function that you use in the HOPFIELD neural network ?

Author's reply :

The cost function used in the adaptive strike planner is used in the route planner. The Jet Propulsion Laboratory (JPL) HOPFIELD net is used in the strike planner, so the cost function is not used in the HOPFIELD net.

The cost function is primary a matrix which is the weighted sum of the information matrices $C_{i,k} = \Sigma\ w_i\ \ I_{i,k}$. The information matrices are typically values assigned to grid cells overlaying a map of the region of interest.

Typical information matrices are threat type air location (probability of shooting down our asset), terrain (probability of hiting the ground) and no fly zones. Of course, you may have information on air aspect you wish.

CONSTRAINTS ON ESM RECEIVERS FOR LPI RADAR APPLICATIONS

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SUMMARY

This paper discusses typical requirements for a Low Probability of Intercept (LPI) radar Electronic Warfare Support Measures (ESM) receiver. A graphical technique is presented for assessing the effects of those requirements on the realizability of the receiver. It is shown how this technique can be used to derive a set of consistent system specifications.

LIST OF SYMBOLS

B_I	bandwidth for measuring pulse density N_D
B_{rf}	radio frequency bandwidth of a channel
B_v	video bandwidth
F	receiver total instantaneous bandwidth
F_r	required accessible bandwidth
F_n	receiver noise figure
G_A	receiver antenna gain
G_s	system gain, the ESM receiver figure of merit
k	Boltzman's constant
N	number of frequency-angle cells to be searched
N_D	incident pulses per second per B_I
N_p	average number of pulses in a given frequency-time cell
P	number of independent spatial views by ESM set
P_D	probability of detection
P_{fa}	probability of false alarm
$P_{max}\|_{CW}$	maximum value of P given CW conditions
$P_{max}\|_{pulse}$	maximum value of P given pulse conditions
PRI	radar pulse repetition interval
q	the number of frequency channels
S	incident signal power in dBmi
SNR	signal-to-noise ratio
T_D	typical radar dwell time
T_o	standard temperature
W_{res}	pulse width measurement resolution
γ	ratio of pre to post detection bandwidths
ω	frequency scan rate

1 INTRODUCTION

Electronic Warfare Support Measures (ESM) systems are required to determine the Electronic Order of Battle[1]. To perform this task, the ESM receiver must intercept emissions from all radars in the vicinity, and measure parameters such as frequency, time-of-arrival, and angle-of-arrival. The measured parameters are collected and analyzed to classify all the transmitted waveforms in the environment. Libraries of particular radars' waveforms are used to identify the potential types of radar equipment which could have produced that classification. Libraries can also be used to determine the radar platform type, affiliation, and threat to the ESM host. An ESM capability enables the host to establish an all weather passive surveillance of surface and air platforms which are actively transmitting radar signals.

A number of technologies are applicable to ESM set receivers[2]. Evidence suggests the predominant technological solutions in current generation naval systems are based on instantaneous frequency measurement (IFM) devices[3]. IFM devices are widely available with octave or more bandwidths over the microwave and millimetre wave bands[4]. They provide efficient spectral coverage and, with modern technology, can very cost-effectively be integrated with an array of crystal video detectors, or detector logarithmic video amplifiers, to provide full 360 degree wideband detection and measurement[5]. The sensitivity of such ESM receivers is usually limited to approximately -55 dBmi to -65 dBmi. This is adequate to detect signals from most pulsed radars at distances exceeding the detection range of the radar. Hence ESM sets are said to have a range advantage over the radar. The range advantage of ESM sets arises from the fact that radars have to cope with a two-way, R^4-law propagation, while the ESM set is only coping with a one-way, R^2-law propagation.

Radars which apply technologies and techniques to avoid detection by ESM sets are termed to have a Low Probability of Intercept (LPI) capability[6]. These techniques can be broadly categorized into three classes: parameter agility, sidelobe control, and lowering the mainbeam equivalent isotropic radiated power (EIRP).

Presented at an AGARD Meeting on 'Challenge of Future EW System Design', October, 1993.

Parameter (and in particular frequency) agility can be effective as an LPI technique against ESM receivers which scan the environment. Wideband/360 degree IFM-based ESM receivers are not vulnerable to frequency, or any other parameter, agility from the point of view of intercepting the emissions, although individual radar transmissions may be more difficult to isolate and characterize.

If the ESM set host is a potential target of the radar, it is reasonable to assume that the ESM set will be illuminated by the main beam of the radar, at least during the radar's surveillance mode. If the sidelobes are below receiver sensitivity, then scanning ESM receivers will suffer from the well-known "scan-on-scan" loss in probability of intercept[7], but again, the wideband/360 degree IFM receiver will consistently detect the main beam illuminations. Hence low radar sidelobes will not prevent detection, and subsequent analysis by modern ESM sets, of sufficient data to adequately determine the Electronic Order of Battle.

To prevent interception, the radar main beam EIRP must be reduced to the point whereby the power density at the ESM antenna is below the sensitivity of the ESM receiver. Radar detection considerations largely limit the ability of the radar designer to substantially reduce the mean power of the radar. However, if the radar can tolerate lengthy transmission times, then the peak power can be economically reduced by increasing the radar duty cycle. Typically, conventional unmodulated-pulse radars have duty cycles of the order of 0.1%. By moving towards modulated continuous wave (CW) waveforms, the peak power can thus typically be reduced by 30 dB[8]. Essentially, the radar receiver can utilize knowledge of the pulsed waveform modulation to efficiently extract the pulse echo from noise, whereas the ESM receiver is unlikely to have any a priori knowledge. The radar advantages of encoding the transmitted pulse have been known for many years[9]. For instance, "chirp", and other modulations, are commonly used to achieve a desired range resolution while reducing peak power requirements. By transmitting pulses with time-bandwidth products much greater than unity, the transmitted/received pulse width can be stretched to increase the duty cycle without sacrificing the bandwidth necessary for range resolution. When the peak power is reduced to a level whereby the radar pulse falls below the detection threshold of the ESM set, then the radar is truly "LPI". Radars with LPI capabilities and operationally useful detection and discrimination specifications for Naval missions are currently commercially available[10]. However, this LPI capability will impose constraints on the radar parameters. In order to detect such LPI radars, new ESM receiver architectures are required which will exploit those constraints.

The remainder of this paper discusses how the requirements on an LPI radar ESM receiver can be translated into a system specification, and the trade-offs and constraints facing the system designer. The discussion focusses around typical requirements likely to be applicable to an ESM set hosted on a Naval surface vessel.

2 LPI RADAR ESM SET REQUIREMENTS

A summary of a typical set of performance requirements for the receiver is shown in table [1]. These parameter values were chosen to illustrate the translation to a system specification, and though the following paragraphs justify the values, defining the actual requirements for a particular user and mission entails a detailed threat assessment which is beyond the scope of this paper.

2.1 Sensitivity and Dynamic Range

Required sensitivity has been estimated[8] as approaching -100 dBmi. *This is approximately 40 dB better than can be* achieved with most wideband IFM-based systems. Hence to avoid gaps in coverage, the LPI radar ESM receiver requires a dynamic range of nominally 40 dB.

2.2 Intrapulse Modulation

LPI radar intrapulse modulation bandwidth for radars of interest to a surface vessel is expected to remain in the order of a few to a few tens of megahertz. Radar range resolution is inversely proportional to bandwidth[11]. Bandwidths less than a few megahertz are unlikely to have sufficient resolution to distinguish slow moving targets from clutter. Bandwidths greater than a few tens of megahertz lead to significant additional data processing in the radar, and can negatively affect the radar cross-section of targets of interest.

2.3 Frequency Coverage

For the purposes of this paper, the required minimum frequency coverage for the LPI radar ESM receiver has been estimated at 4 GHz. It is believed that LPI radars are most likely to be relatively short range, perhaps a few 10s of km, otherwise the R^4 versus R^2 propagation law will negate attempts at LPI by the radar designer, and it is believed unlikely that short range radars will be designed to operate in the lower portion of the microwave spectrum. The very high end of the spectrum is thought to be too lossy and subject to atmospheric attenuation for most LPI radars. Hence the frequency coverage can be constrained to a fraction of that required by ESM receivers for non-LPI radars.

2.4 Pulsed versus CW Detection

An important consideration is whether the LPI radars of interest are all CW or whether pulsed LPI is also a consideration. If pulsed radars are of interest, then the minimum pulse width that is guaranteed detectable by the ESM receiver and the PRI of the radars must be specified. For conventional radars, minimum pulse widths on the order of 10 ns to 100 ns are required, with typical pulse widths on the order of 1 μs. It is expected that LPI radar signals will be substantially longer than conventional radar pulses to take advantage of pulse compression/spread spectrum techniques for reducing the peak power. For illustrative purposes in this paper, a minimum pulse width requirement of 20 μs has been chosen. As discussed previously, LPI radars are expected to be relatively short range, hence extremely long PRI waveforms are unlikely. For illustrative purposes, a maximum PRI of 1 ms has been chosen for this paper.

2.5 Interference from Conventional Pulses

Enhanced sensitivity will greatly increase the number of conventional radar signals potentially above the detection threshold of the LPI radar ESM receiver. These conventional signals are largely unwanted, and constitute a potential source of interference. The receiver must be able to differentiate between these interfering signals and the wanted high duty cycle, LPI emitters. The density of interfering conventional pulses will be highly mission dependent. For illustrative purposes in this paper, a pulse density of 1 Mpps per 10 GHz has been chosen.

2.6 Maximum Revisit Time

Given the above sensitivity requirements for main beam detection, it is probably not practical to guarantee sidelobe detection against scanning emitters. Hence if the LPI radar ESM set is also to scan, a maximum revisit interval must be specified to guarantee detection. This maximum revisit interval is dependent upon the LPI emitter main beam illumination duration. As soon as the revisit interval substantially exceeds the main beam illumination duration, then the probability of intercept rapidly decreases. Again for illustrative purposes, a figure of 20 ms has been chosen as the specification value.

3 THE SOLUTION SPACE

The sensitivity of a receiver, measured in dBmi, is largely determined from four quantities: pre-detection noise bandwidth, video bandwidth, antenna gain, and system noise figure or effective temperature. For most ESM applications, noise figure is adequate to characterize the noise, and hence effective temperature will not be used in this paper. In practice, the difference between the two approaches is unlikely to make more than a dB or so of difference in the predicted performance. The antenna gain and system noise figure can be combined into a single figure-of-merit, which represents the increase in signal-to-noise ratio achieved by the receiver relative to an ideal omni-directional receiver. In further discussion, this figure of merit is simply referred to as the gain, G_s, of the system. Hence,

$$G_s = G_A/F_s \quad ...1$$

The system gain is expressed in dB relative to an ideal receiver with a lossless, omni-directional antenna.

The pre-detection noise bandwidth represents the bandwidth of RF space visible at an instant of time. In a channelized architecture (see para. 4.5) the total instantaneous bandwidth is the pre-detection bandwidth multiplied by the number of simultaneous channels. Hence although the pre-detection bandwidth is probably centred on an intermediate frequency, it represents an instantaneous RF bandwidth.

Following Tsui[2], the ratio of pre-detection to post-detection bandwidth is defined as γ.

$$\gamma = B_{rf}/B_v \quad ...2$$

The process of detection is statistical in nature, and can only be defined in terms of statistical quantities. In particular, the probability of detection and the probability of false alarm, for a given signal-to-noise level, uniquely define the operating characteristics of the detection process for a given ratio of pre-detection to video bandwidths. Tsui[2] presents a series of charts for values of γ between 1 and 900. Each chart is for a particular value of γ, and plots the probability of detection versus signal-to-noise ratio for several values of probability of false alarm. It is implicit in these charts that the detection process is thermal noise limited. The accuracy of these charts is estimated as 1 dB.

For this work, particular values of detection and false alarm probabilities were chosen as shown:

$$P_D = 0.9$$

$$P_{fa} = 10^{-6}.$$

The graphs in [2] can then be used to generate a table of required SNR as a function of γ. This is presented here as Table 2, and is estimated to be accurate to about 2 dB. It was found heuristically that the value of γ at low SNR could be well approximated from the equation:

$$10\log_{10}\gamma = -1.6.\text{SNR(dB)} + 20.$$

The solution space for the receiver is that which shows all possible combinations of RF bandwidth, video bandwidth, and system gain. Figure 1 graphs the RF bandwidth versus the video bandwidth over several decades of parameter space. Lines of constant γ are straight, parallel lines inclined at 45 degrees. As the detection statistics relate required SNR to γ, these inclined lines also represent lines of constant required SNR. For the given signal strength in dBmi, the SNR is dependent only upon the RF bandwidth and the system gain.

$$SNR = S.G_s/B_{RF}.kT_o \quad ...3$$

Thus for every point in B_{RF} versus B_v space, there is a unique required value of G_s to meet the required P_D and P_{fa} for the specified sensitivity. Lines of constant required G_s form contours connecting the lines of constant γ. A number of these contours are plotted on Figure 1. This figure represents the complete solution space for the given detection requirements. For any point in the B_{RF}/B_v space, the required system gain can be interpolated.

The primary problem for the ESM systems engineer is to determine where in this solution space an actual receiver should be located.

4 CONSTRAINING THE SOLUTION SPACE

The solution space described by Figure 1 is constrained only by the requirements defining sensitivity. This section shows how the other requirements of Table 1 constrain the available options.

4.1 CONSTRAINT ON MINIMUM PRE-DETECTION BANDWIDTH (Modulation Bandwidth Effect)

If the signal spectrum is not constrained within the pre-detection bandwidth, then an additional detection loss will be incurred. In the limit, if the pre-detection bandwidth becomes less than the signal spectral width, then the detectable signal energy will become proportional to the receiver bandwidth, similar to noise. In the case of FMCW LPI signals, the spectral bandwidth may be quite narrow over the video decorrelation time, but for phase modulated LPI signals the full spectral width will be present at all times. This tends to limit the usefulness of very narrow band pre-detection solutions. Given typical radar pulse bandwidths, there is a diminishing return for pre-detection bandwidths less than about 20 MHz. This can be plotted as a straight, horizontal line on Figure 1.

4.2 CONSTRAINT ON MINIMUM POST-DETECTION BANDWIDTH (Minimum Pulse Width Effect)

The ability to measure short pulses with the required sensitivity depends upon the post-detection video bandwidth. If the video bandwidth is too low, then additional losses are encountered, akin to matched filter losses in a radar. Pulse width measurement is a potential way of differentiating between LPI emitters and conventional more distant emitters. Pulse width measurement resolution is also dependent upon the video bandwidth. The resolution is approximately given by,

$$W_{res} = B_v^{-1} \quad ...4$$

and the minimum pulse width is twice the pulse width resolution. Thus in order to be able to measure pulses as short as 20 µs, a video bandwidth of at least 0.1 MHz is required. This minimum video bandwidth constraint can be plotted as a straight vertical line on Figure 1.

4.3 CONSTRAINT ON MAXIMUM γ (Interfering Pulses Effect)

Any high sensitivity LPI receiver is going to be vulnerable to interference from conventional distant emitters masking the pulses from emitters of interest. The pulse density N_D, is defined as the total number of incident pulses per second in a band B_I. The average number of conventional pulses occurring in the frequency band B_{RF} and time duration B_v^{-1} is given by:

$$N_p = N_D.B_v^{-1}.B_{RF}/B_I \quad ...5$$

$$= N_D.\gamma/B_I \quad ...6$$

Taking the nominal values of 1M pps per 10GHz gives:

$$N_p = 10^{-4}.\gamma$$

In order to keep the number of frequency/time cells corrupted by conventional emitters down to not more than a few percent, γ has to be restricted to not more than a few hundred. As described previously, lines of constant γ are also lines of constant required SNR, and a γ of 300 corresponds to the 3 dB line in Figure 1. Lines of higher γ, and consequently higher required SNR, will have correspondingly higher percentage corruption by conventional pulses.

4.4 CONSTRAINT ON MAXIMUM SYSTEM GAIN (Revisit Interval Effect)

The system gain is set from the receiver noise figure and the available antenna gain.

With regards to noise figure, such a highly sensitive receiver as required for LPI radar detection will probably require a low noise amplifier (LNA) as close as possible to the receiving antenna. However, in a naval environment, receiver protection devices will almost certainly be required to protect against own ship illuminations. In practice, signal processing losses, for instance due to constant false alarm rate (CFAR) circuitry, must also be accounted for. It is thought unlikely that the noise figure can be reduced below 5 dB.

With regards to the antenna gain, for a naval application it is probable that 360 degree azimuthal coverage will be required, with elevation coverage of approximately +/- 25 degrees. Achieving this beam pattern with a single (omni) antenna will limit the antenna gain to about -3 dB, or perhaps 0 dB on boresight. Additional gain can be achieved by scanning a directional antenna in azimuth. In order to guarantee scan-on-scan intercept, the ESM antenna beam must be swept around within the illumination period of the radar. A typical illumination period of 20 ms then requires a minimum ESM set antenna scan rate of 50 Hz. If the ESM set receiver is scanning in frequency also, or multiple detections are required to confirm detection, then the beam scan rate must increase proportionally. The rather high resultant scan rates imply that mechanical beam scanning is probably not practical, and only electronic scanning need be considered further. Electronic scanning may be most conveniently implemented by stepping the beam through a sequence of overlapping locations. It is assumed here that any beam scanning is implemented as a sequence of stepped positions overlapped at their 3 dB points. The number of steps to cover the full coverage is defined as "P". The greater the value of "P", the greater the antenna gain will be. Table 2 shows approximate values that can be expected for antenna gain as a function of "P".

If emitters of interest are CW only, then the dwell period in any particular direction is only limited by the requirement to settle the video filters. Allowing 2 B_v^{-1} seconds per location, gives a maximum value of:

$$P_{max}|_{CW} = T_D/(2.B_v^{-1}) \quad ...7$$

$$= T_D.B_v/2 \quad ...8$$

Thus we now have a relationship between the video bandwidth and the antenna, and hence the system, maximum gain. This can be plotted on Figure 1, and will form a constraint on the solution space.

If pulsed emitters are also of interest, then the solution space becomes further constrained. To guarantee coincidence of the beam and a pulse, the beam must be dwelled for approximately the PRI of the transmitting radar. In this case,

$$P_{max}|_{pulse} = T_D/PRI \quad ...9$$

Typically, one might expect values of 20 ms and 1 ms for T_D and PRI respectively, giving a peak value for "P" of 20. This can be plotted on the graph of Figure 1 by relating P to the achievable system gain. Similarly to the CW case, any frequency scanning will proportionally affect the maximum value of "P".

In practice, experience indicates that other, more prosaic, considerations will also play their part in limiting the maximum value for "P". Multiple beam positions can be expensive to implement, especially if each position requires its own receiver protection and LNA, etc. Thus, in some cases it may be seen to be prudent to limit "P" to no more than about eight. This will further limit the solution space.

4.5 CONSTRAINTS ON THE INSTANTANEOUS BANDWIDTH "F"

A number of channels may be implemented in parallel to broaden the instantaneous bandwidth. Given q channels, the instantaneous bandwidth is taken to be:

$$F = q.B_{rf} \quad ...10$$

The maximum frequency scan rate of a single channel is given by the product of the pre- and post-detection bandwidths. Hence for q parallel channels the maximum system frequency scan rate is approximately given by:

$$W = q.B_{rf}^2/\gamma \quad ...11$$

In the case where the system is only required to detect CW LPI radar emissions, then in principle it need dwell no longer at any one location than that dictated by the maximum scan rate. In practice, allowance must be made for switching times and possible "m out of n" detection schemes. Here we will assume two consecutive detections are required, but that switching times are neglible. Given the requirement to scan a total accessible bandwidth of F_r, and a total of P spatial locations, within the LPI radar dwell time T_D, an inequality can be derived linking γ with B_{rf}.

In order to scan the frequency/azimuth space within the radar illumination time:

$$T_D \geq F_r.P/W \quad ...12$$

thus:

$$B_{rf}^2 \geq 2.F_r.P.\gamma/q.T_D \quad ...13$$

Of these terms, F_r and T_D are requirements. If P and q are set, for instance by available technology, then the minimum value of B_{rf} is only dependent upon γ. Hence a contour can be drawn on Figure 1 constraining the solution space. Alternatively, if q is to be determined, a third axis can be constructed and the minimum value of q calculated for every point in the B_{rf} - B_v plane. The number of channels will then be viewed as a surface over the plane.

If the ESM set must also detect non-CW LPI emitters, then the minimum dwell time in any frequency-angle cell must be extended to approximately a full PRI. The total number of frequency-angle dwells that the ESM set must make to search the entire space is given by:

$$N = F_r.P/q.B_{rf} \quad ...14$$

and to search that space and guarantee interception:

$$T_D \geq N.PRI \quad ...15$$

Thus:

$$q \geq F_r.P.PRI/T_D.B_{rf} \quad ...16$$

or

$$F \geq F_r.P.PRI/T_D \quad ...17$$

Given constraints on the total frequency coverage, the maximum PRI of interest and the minimum LPI radar illumination time, the total instantaneous bandwidth can be computed as a function of "P" only. As "P" is directly relatable to the system gain, the minimum instantaneous bandwidth can also be plotted directly on Figure 1.

5 CONCLUSIONS AND IMPLICATIONS

The graphical techniques presented here in Sections 3 and 4 have been applied to the example set of requirements described in Section 2. The resultant constrained solution space is shown in Figure 2. It can be seen that the range of options available for the system designer have been drastically reduced. This technique can be rapidly applied to different sets of requirements, firstly to assess whether the requirements are compatible (i.e., some portion of the solution space remains open), and secondly to convert the requirements into specifications on the bandwidths, gains and number of antenna ports defining the ESM receiver performance. The graph can also be used as a tool to assess the trade-offs involved with changing operational requirements, or alternatively assessing the applicability of different technologies to the LPI radar ESM problem. Although the discussions here have focussed specifically on the LPI radar ESM problem, this graphical approach is also applicable to analysis of conventional radar ESM receiver architectures.

Lockheed Canada, with funding from the Canadian Defence Research Establishment Ottawa, has derived an architecture and initiated breadboard design activities around an existing channelizer for LPI radar detection. The techniques presented here were used to analyze the system requirements. The baselined channelizer for the breadboard has an instantaneous bandwidth of nominally 500 MHz, divided into 27 contiguous channels. Detailed characteristics of the channelizer have been reported previously in the open literature[3].

ACKNOWLEDGEMENTS

The author would like to acknowledge Dr. J. Lee from the Canadian Defence Research Establishment Ottawa, who sponsored the project leading to this paper and provided constructive criticism throughout.

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REFERENCES

[1] The Strategy of Electromagnetic Conflict: Ed. Lt. Col E. Fitts, Peninsula Publishing, 1980.

[2] Microwave Receivers with Electronic Warfare Applications: Tsui J. B., Wiley-Interscience , 1986.

[3] ESM Systems - Coping with Dense Electromagnetic Environments: Self A. G, Cooper R. T., and Park G. G., Proc of the 1990 AOC NE Region Symposium, Ottawa 1990.

[4] D.Heaton,'The Systems Engineer's Primer on IFM Receivers,' Microwave Journal, Febuary 1980.

[5] Low Cost ESM - What Technology Opportunities?, Self A. G., Radar 1992 Conf Proc, pp 175-179, London 1992.

[6] LPI Considerations for Surveillance Radars: Ruffe L. I. & Stott G. F, Radar '92 Conf Proc, pp 200-202, London 1992.

[7] Self,A.G., Smith B.G.:'Intercept Time and its Prediction', IEE Proc., Vol. 132, Pt. F, July 1985, pp215-222.

[8] Lee, J. P., "Interception of LPI Radar Signals," Defence Research Establishment, Ottawa, Ontario, Report # DREO-TN-91-23, Nov 1991.

[9] North, D. O.: An Analysis of the Factors Which Determine Signal/Noise Discrimination in Pulsed Carrier Systems, RCA Tech Rept PTR-6C, 25 June 1943 (ATI 14009). Reprinted in Proc. IEEE, vol 51, pp 1016-1027, July 1963.

[10] The Scout Radar brochure, Signaal 1991, FO.0135.

[11] Introduction to Radar Systems, Skolnik M. I., McGraw-Hill, 1980.

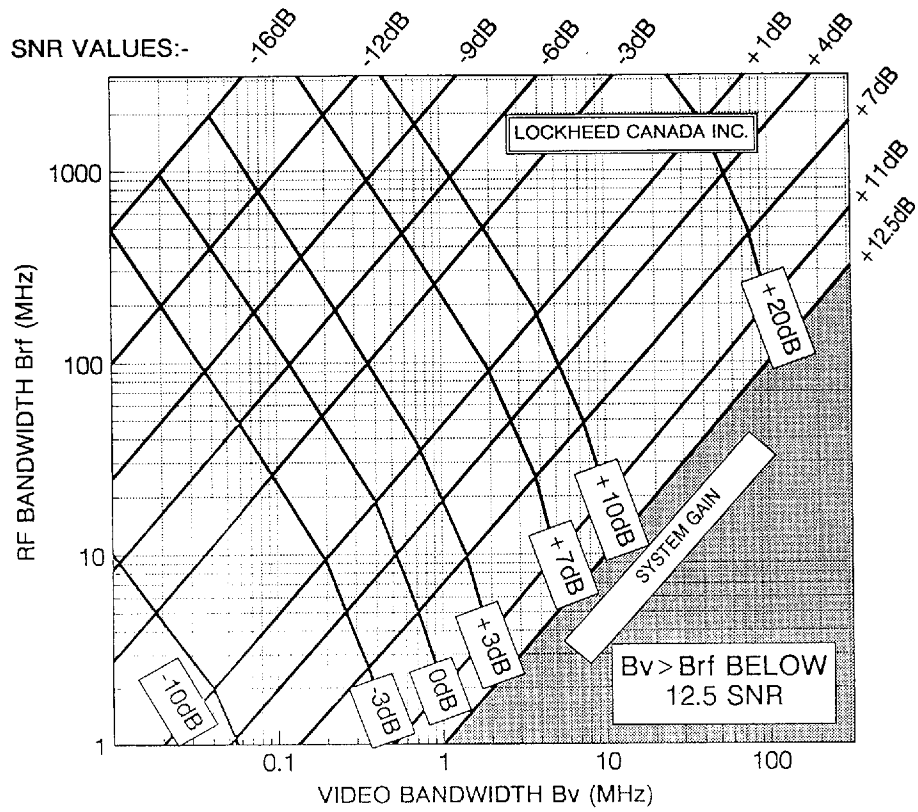
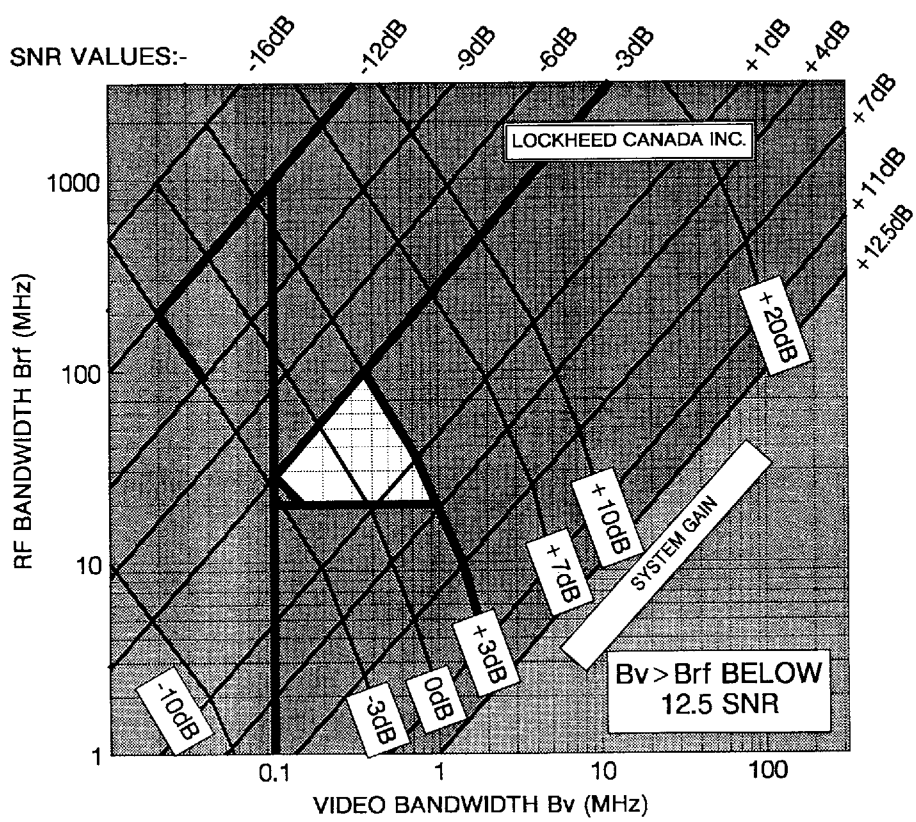

SNR VALUES:-
-16dB
-12dB
-9dB
-6dB
-3dB
+1dB
+4dB
+7dB
+11dB
+12.5dB
LOCKHEED CANADA INC.
1000
100
10
1
RF BANDWIDTH Brf (MHz)
+20dB
+10dB
+7dB
+3dB
0dB
-3dB
-10dB
SYSTEM GAIN
Bv>Brf BELOW
12.5 SNR
0.1
1
10
100
VIDEO BANDWIDTH Bv (MHz)

Fig.1


SNR VALUES:-
-16dB
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-3dB
+1dB
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+3dB
0dB
-3dB
-10dB
SYSTEM GAIN
Bv>Brf BELOW
12.5 SNR
0.1
1
10
100
VIDEO BANDWIDTH Bv (MHz)

Fig.2

Table 1 LPI RADAR ESM SET TOP LEVEL REQUIREMENTS

Sensitivity	-100 dBmi
Dynamic range	40 dB
Intrapulse	10s of MHz
Frequency coverage	4 GHz
Pulsed emissions	20 microsecond min PW nominally 1 ms max PRI
Interference	1 Mpps per 10 GHz (above -100 dBmi)
Revisit interval	20 ms

Table 2 REQUIRED SNR VS γ

Required SNR (dB) (90% P_d & 10^{-6} P_{fa})	-6	-3	1	4	7	11
B_{rf}/B_v (γ) from graphs in [2]	900	300	50	20	6.5	2
B_{rf}/B_v (γ) using equn.	912	302	69	23	7.6	1.7

Table 3 AVERAGE ANTENNA GAIN VS # OF SPATIAL LOOKS

Number of antenna ports "P"	4	8	16
Best possible average gain (dBi)	5	8	11

Discussion

DISCUSSOR : **M. H.K. MARDIA (UK)**

In the analysis of interfering signals, what consideration was taken for the pulse-width distribution ?

Author's reply :

Due to the small video bandwith, the effect of narrow pulses is negligible.

FUSION OF ESM, RADAR, IFF DATA AND OTHER ATTRIBUTE INFORMATION FOR TARGET IDENTITY ESTIMATION AND A POTENTIAL APPLICATION TO THE CANADIAN PATROL FRIGATE

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ABSTRACT

Electronic support measure (ESM) and the communication intercept operation (CIO) are traditionally used to perform the task of target identification. Today, targets are more sophisticated and inclusion of other means to assess identity are necessary. It is thus natural to desire to fuse information available from all possible sources onboard a platform in order to evaluate the target identity. This paper presents and outlines the sensor technologies involved in the measurement of attribute information pertaining to targets. The output data of these sensors are analyzed in terms of their contribution to a fusion algorithm that fuses attribute data to extract target identity in order to improve the EW functionality of an AAW frigate. It is observed that currently available ESM, CIO and IFF are specifically designed to provide automatically attribute information but surveillance radars and IRST are not. However surveillance radars and IRST are theoretically, capable of attribute measurement. The analysis shows how to fuse the sensor attribute information using a truncated version of the Dempster-Shafer evidential theory. This fusion technique is similar to the exact formulation except that the combination rules include some approximations and pruning. Since the combination of attribute information creates several identity propositions it becomes necessary to constrain the combination rules. The method is applied to a simple scenario and the advantages and disadvantages of the fusion method are discussed and compared with the exact formalism. This paper discusses how the type of attribute data received from the sensors of the Canadian Patrol Frigate specifically the ESM and IFF can be fused using these techniques.

1 Introduction

Paramax Systems Canada is the systems integrator for the Canadian Patrol Frigate (CPF) and the New Shipborne Aircraft (NSA) programs. These platforms have distributed automated Command and Control Systems (CCSs), where the processed contact and track data from the various sensors are correlated and consolidated into a centralized database and made available for use by the various CCS functions, such as Tactical Situation Display, Electronic Support, Radar Control, Acoustic Control, Fire Control, etc. However, the operators still have a significant role in the integration and interpretation of the data provided by its multiple and dissimilar sensors. The demands placed upon the Combat System to integrate and interpret the tactical data within the threat environment of the future are foreseen to be beyond human capability [Waltz and Buede, 1986]. This stresses the necessity to develop platforms which will make better use of automated CCSs that will integrate technologies such as Multi-Sensor Data Fusion (MSDF).

The Joint Directors of Laboratories Data Fusion Subpanel of United States has defined data fusion as: "A process dealing with the association, correlation, and combination of data and information from multiple sources to achieve refined position and identity estimation, and complete the timely assessments of situation and threats, and their significance". This paper focuses on the problem of Identity Estimation within an MSDF system.

Until now sensor designers have developed sensors such as Medium Range Radar (MRR), Long Range Radar (LRR), Electronics Support Measure (ESM), Interrogation Friend or Foe (IFF), etc, in a single sensor context. This means that sensors are expected to provide only useful and complete results. For example, for target identity, a complete result is a target type declaration based on a set of measurements which is complete and unambiguous. A subset of such a measurement set does not necessarily lead to nor have to lead to useful conclusions in the stand alone single sensor context. Also sensors are expected to derive maximal conclusions about their measurements. This explains why a surveillance radar which is in fact a chronometer measuring range is also required to estimate state vectors, covariance matrix, etc. With the advent of fusion, a new philosophy of design and sensor data processing can be added to the sensors. The sensors can now make available to external algorithms incomplete sets of data. A group of many incomplete sets of data from many sensors may be fused and lead to useful and unambiguous declarations. This effect obtained from the fusion is called synergy.

The literature search performed within this research shows that the IFF sensor AN/UPX-30 is probably the first sensor which attempts to fuse information from other sensors [See discussion about AN/UPX-30 in Poinsett and Schmiedeskamp, 1988]. The British Royal Navy started six years ago the Electronic Warfare Central Processor (EWCP) project where fusion techniques will be utilized to increase the performance of the ESM sensor [Royal Navy EWCP, 1992]. Recently in Canada, a similar project [DREO EWCP, 1992] has been started. The US Navy is also working on a multiple platform project of fusion to increase ESM capability [Delong, 1992]. All these projects are aiming to maximize the capability of a specific sensor. Fusion cannot be considered as a sophisticated IFF or ESM system, it can do more. Fusion can be tailored to maximize the performance of command

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and control systems (CCS). This provides more advantages. For example, data association can be performed between attribute type and positional type of information, identity estimation can help state estimation and vice-versa. Such fusion function is currently under trial in the US Navy, which developed a fusion function combining ESM, Forward Looking Infra-Red (FLIR) camera, radar and a tactical data link [Scott, 1992] for a fighter aircraft. The opinion of Command and Control (C^2) platform designers is that fusion techniques should be implemented within the C^2 separately and independently from the sensors. This will ensure maximal performance and flexibility for future implementations and upgrade.

The aim of this paper is to show how the attribute information obtained by the sensors of a frigate size AAW ship may be fused to extract a target identity. The sensor suite which is considered here consists of a two surveillance radar LRR and MRR, an Infra-Red Search and Track (IRST) sensor, an IFF sensor and an ESM sensor. The positional fusion process will be also considered as a source of attribute information and will be used in the attribute fusion process. Two techniques of fusion are discussed and compared. One is the Dempster-Shafer evidential theory, called the exact version, while the other approach is an approximation of the same, named truncated version. The sensors as well as the Platform Data Base (PDB) requirements are detailed and explained.

These analyses have been performed to garner knowledge for the design and implementation of the Multi-Sensor Data Fusion (MSDF) system demonstration model within the real-time Command and Control Systems (CCS) environment of the Combat System Test and Support Facility (CSTSF) at Paramax, contracted by the Department of National Defence (DND) Chief of Research and Development (CRAD), aimed at the mid-life upgrade of the CPF. This paper presents theoretical analyses for target identity estimation and then discusses how the type of data received from the sensors of CPF specifically the ESM and IFF can be fused within this system.

2 Preliminary Concepts

There are some concepts about fusion which are fundamental and which must be clarified first. The term attribute data and sensor fusion architecture are among these. Before a fusion function can be implemented within a combat system, the possible sensor fusion architectures and implementations must be explored. The benefits and drawbacks of these implementations and how all this relates to the performance and mission requirements of the platform must be analyzed.

The technological advancement of future threats to the Navy (faster, stealth, etc.) has caused a reevaluation of how sensors should be integrated and their role in the data measurement and decision processes. The surveyed literature addresses different benefits in terms of increasing the processing gain derived in surveillance systems by combining the data and target class declarations using multiple sensors. The performance improvements have been demonstrated on a number of multiple sensor data fusion simulation systems for certain simple applications. Mathematically, as a special case, the use of classical bayesian estimation techniques [Nahin and Pokoski, 1980] proves that for identical and statistically independent sensors, more sensors improve performance.

Many different ways to combine data from multiple sensors have been investigated. Depending on the way the sensor data are combined, the benefits are different. The combat system performance requirements differ from platform to platform and from mission to mission. Therefore, the selection of the sensor fusion architecture should be aimed at optimizing the system target detection, tracking and identification performance required for the differing missions of the platform. The selection of the sensor fusion architecture is also constrained by the hardware and software technological capabilities of the sensor and command and control systems. The two sections of this chapter aim to define and explain terminology and to discuss about the consequences of the sensor fusion architectures.

2.1 Positional Information and Attribute Information

Positional information constitutes the dynamical parameters describing the movement of a target. This generally includes position, speed and acceleration with the appropriate covariance information. A sensor which is tailored to measure positional information measures directly some component of the position (range or azimuth or elevation) and derives indirectly the rest of the information, the speed and the acceleration. The derived information is not measured by the sensing device as opposed to the position parameters. This information is estimated by some algorithms which perform statistical analysis on dynamical random variables to get the target state vector and its covariance matrix. The measured, as well as the estimated parameters, are treated as dynamical random variables. The positional information has two statistical characteristics: 1) each dynamical parameter takes any value on a continuous space (observation area); and 2) a concept of standard deviation is applicable to each. Depending on the sensor suite, fusion of positional information may be performed by using advanced tracking algorithm. It was recently pointed out that one of the main advantages of positional fusion is the tracking of target in almost electromagnetically silent mode [Bégin, Simard and Valin; 1993]. This kind of fusion is not treated here. Details may be found in many good monographies specificaly devoted to this subject [Bar-Shalom, 1990 and 1992; Hall, 1992].

Attribute information is somewhat harder to define mathematically since the format of this kind of information is disparate. In order to embrace all the formats generated by the different sensors, the attribute information will be defined as: declarations, propositions or statements that contribute to establish the target classification or the target identity. This definition is adapted from the definition given in [Wilson, 1985] and complies with the examples presented in most of the literature about sensor data fusion, see for example [Waltz and Llinas, 1990]. Table 1 below presents various kinds of attribute information which can be obtained from different sensors. For the purpose of the analysis, this table contains all types of sensors that could be part of the sensor suite of a relatively large AAW ship. Most of them can be found in a modern AAW frigate but due to operational and mission limitations, it will be unlikely that some of these, such as the synthetic array radar (SAR) or the inverse synthetic array radar (ISAR), be implemented today or in the near future on a frigate size ship.

Table 1 Attribute Information from various AAW sensors

Attribute information	Sensor or Process
Emitter type	ESM
Allegiance	IFF
Target type based on elevation Size based on RCS Symmetry based on echo polarization Moving part based on echo modulation	Surveillance radar
Target type based on elevation Infrared spectrum	IRST
Target shape and moments	EO or IR Camera
Textual information (language, speaker, Key words)	CIO
Speed and acceleration characteristics	Positional Fusion
Image based on coherent RCS	SAR or ISAR

The first two sensors listed, ESM and IFF, are probably the most commonly used sensors for the purpose of target identification. An ESM sensor measures the physical characteristics of any electromagnetic radiation and associates the measured parameters to one or more emitter types, listed in a data base specifically designed for this purpose. The output attribute information from the ESM, at the signal level processing (see next section), is a declaration about one emitter or a list of emitters with an appropriate level of confidence. For example the ESM declaration can be of the following form: "**radar AN/SPS-49 with 60%** confidence". The assigned level of confidence should not be interpreted as a probability measuring the degree of truth, rather as a subjective measure of the matching degree between the measured and the data base listed parameters. For all sensors or sources the interpretation should be the same in theory.

The attribute data are statistically different from the positional data. They usually do not belong to a continuous space. In most cases, they pertain to a space of discrete values to which the concept of standard deviation is not applicable. When a surveillance radar reports the range of a contact, the information is in the form of "$R \pm \sigma_R$ ". This has a very precise meaning. To this number, various well understood statistical tests can be applied for correlation purposes for example. However, attribute data can not be treated the same way. When an ESM sensor reports that a detected emitter is an AN/SPS-49, this information is a declaration (or a proposition) which is not a number with a physical dimension. The "value" that the declaration can take is discrete and has no standard deviation.

Another declaration, from a radar for example, can be of the form "**it is a small target**". The word small can be visualized as an indication of the radar cross section (RCS). This appears confusing since the RCS is a continuous and a dimensional quantity, and to which a standard deviation measure can be associated. In spite of the capability of the radar to measure accurately the RCS, in general the declaration will be considered as a "fuzzy" statement where the word small refers to an order of magnitude. The space domain of the fuzzy statement is not necessarily continuous and the concept of standard deviation is not applicable.

Contrary to positional information, a good sensor accuracy or resolution performance in the primary parameter measurement process, will not necessarily yield high quality attribute information. If a radar has accurately measured an RCS equal to $4.25 \pm 0.02\ m^2$, this does not confirm that the target is small. In this example the RCS is a continuous random variable, and in addition, as the smallness of the ratio 0.02/4.25 indicates, it could be interpreted as a quite precise information. But in spite of the relatively good accuracy of the measured quantity RCS, the statement "**it is a small target**" may be stated with a very low probability to be true due to the usual RCS dependence on target profile or to the target stealth capability.

2.2 Sensor Fusion Architecture and its Implication

Compared with today's sensors, the first generation of radar and ESM sensors that appeared in the early 1940 had modest processing capability and their roles were limited to target detection at relatively small range [Stimson, 1983; Schleher, 1986]. As the lethality and number of threats increased, more operational and mission requirements were imposed on the sensors. Today, modern radars under development must be capable of detecting potential targets, assess the contact parameters, track the confirmed targets and perform classification based on some attribute measurement. For the future, the sensor designers are required to integrate sensors in systems that combine information (from sensors and from other sources) and to produce higher level of processed output such as the situation assessment and the threat assessment. As the sensors are now capable of many layers of information processing and output complexity the way sensors are connected with each other can permit many architectures.

The Figure 1 below, sketches many different ways the fusion of the information generated by two sensors can be performed. The figure shows a surveillance radar and an ESM sensor, but the discussion is applicable to most of the sensors listed in table 1. The radar is symbolized by the parabolic antenna and the ESM by a cone. The ways that the sensors can handle the measurements are classified into three stages or units: the energy, the signal and the target processing stages. From the first to the third stage the level of abstraction of the input and output information increases. The dashed lines drawn in the figure are not all at the same time connected to a typical fusion function. Here these lines represent alternative choices.

The energy processing unit is responsible for transforming the sensed energy into a "signal", a form more suitable to target detection. A sensor senses only the ambient energy that is induced by the presence of targets and the background noise, and that propagates towards it. Depending on the sensor, the waves that carries energy can be radio waves, optical light, pressure deformation, etc. The energy processing unit transforms the measured energy into a signal by using heterodyning or analog-to-digital circuitry. It does not change the amount of information contained in the received energy. The produced signal is then delayed in time or shifted in frequency and referenced to a standard time or frequency, depending on the sensors.

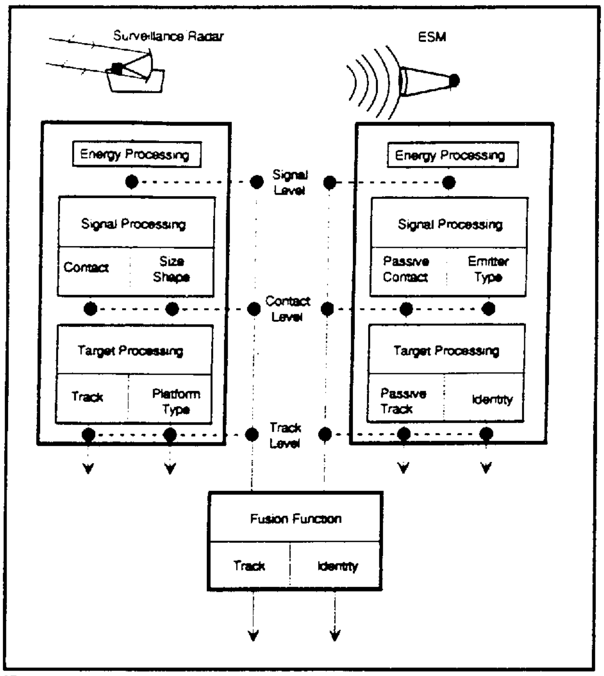

Figure 1 Fusion architectures between a surveillance radar and an ESM sensor

Theoretically, the output information of this stage can be sent to a sensor fusion processor. This is indicated by the dashed lines of the top part of the figure. This fusion architecture is referred to under various names in the literature. The most common one is "pixel level" due to fusion of imaging sensors. For a more general class of sensors a more generic name such as "signal level architecture" is preferable. In such fusion architecture the data alignment problems are extremely complex to solve when dealing with dissimilar or non-collocated sensors. In principle this is only feasible with identical and closely spaced sensors. The words "closely spaced" are relative to the expected target range. In spite of the large distance between each sensor, in astronomy this architecture is widely used for fusion of imaging sensors because the target ranges are of the order of light-year. The new generation of array telescopes and radio-telescopes takes advantage of this fusion level since it provides maximized detection range and optimizes the synergy of the fusion.

The next level of processing comes from the signal processing unit which is responsible for the detection of the targets and the assessment of the contact positional and attribute information. At this stage, an ESM as well as a radar, performs a Fourier transformation on the input signal and computes a signal-to-noise ratio. The goal of this process is to separate the targets from all kinds of non-interesting (noise) features. After this separation is done the positional and the attribute information can be evaluated. The radar will extract a time of arrival on a signal of interest to determine the target range, azimuth and elevation. The RCS as well the signal strength will be extracted and their values will be used to infer attributes about the target size or shape. The ESM will use beam forming techniques on the signal to extract target azimuth and elevation. The time dependence of the signal frequency will be evaluated in many aspects and an inference to an emitter type will be performed. At the end of this process the positional and the attribute information are separated from the input signal and fusion can be performed separately on the both kinds of information as shown by the dashed connection in the middle of the Figure 1.

This fusion architecture is also referred to by many names in the literature. The most common are central level and contact level fusion architecture. Contact level is the name used in this document. At this level, each sensor sends their contacts to the fusion centre and it is the responsibility of the fusion function to get the target track and its identity. The fusion performed at this level provides high quality results but at the price of a large amount of processing. It has the advantage of providing track and identity faster or as fast as any of the sensors connected to the fusion process.

The last stage of processing of a sophisticated sensor is target processing. The target processing unit of a radar is known as the Automatic Detection and Tracking (ADT) function. A modern ESM has a similar high level of processing. This stage of processing is not common to all sensors. An exclusively imaging sensor like an IR camera is not capable of automatic target search and tracking while an IRST as the AN/SAR-8 performs these tasks. At this stage the sensor processes many contacts related to the same target to estimate information of a higher level, such as state vector, covariance matrix, target identity. The fusion performed at this level is known as sensor level fusion architecture. The name "track level" is probably more appropriate in the context of this study since most of the sensors that will be fused have target processing capability.

The fusion at this level is relatively more easy than contact level. The tracking performances are better than those of any single sensor but of a lesser quality than contact level fusion. This fusion architecture is advantageous when many sensors have to be fused, when strongly dissimilar sensors have to be fused or when the computer processing capabilities are limited. For the sensor suite that will be found on the assumed typical modern frigate or destroyer of this study, these restrictions should not apply.

It is possible to fuse the sensor information in many ways, by mixing the three levels of processing from different sensors. For example, as an extreme case, the positional information from the radar can be fused at the track level and the attribute at the contact level while for the ESM the positional information can be fused at the contact level and the attribute at the track level. Such an architecture is a hybrid combination of contact level and track level. Hybrid fusion architecture is advantageous when the fusion processing capability can be hindered by sudden increase in data or in incompatible levels of sensor information. This fusion architecture will be the one assumed in the next chapter where an attribute fusion function which extracts the platform identity of a target will be described.

Before going further, the expressions emitter identity, platform identity and target identity need to be clearly defined. Emitter identity is the object that can be estimated from the measurements performed by an ESM sensor because it detects only the electromagnetic emissions that are radiated from the emitter pertaining to a more structured object called platform. The platform identity is therefore the object that contains the emitter. In its search for an identity ESM consults two data bases, an Emitter Data Base (EDB) which includes a list of potential emitter identities and a platform data base (PDB). The platform data base is consulted because from the point of view of the commander or ESM operator it is more important to know who possesses the emitter than to know the emitter itself. The expression target identity is more difficult to state because there is no standardized definition. This expression is often used in the literature within the context of the studied sensor or system. As an example, for the ESM world a ship's emitter is a target while for an infra-red camera a source of heat such as a ship's funnel is a target. For a data fusion function there is no such concept as sensor's targets but rather sensor attributes measured by various sensors which have to be fused and which belong to a platform which may be considered as the target. In this document, target identity is used to mean platform identity while an object detected by the ESM is called an emitter.

3 Design of an attribute fusion function

Figure 1 shows that a sensor may have its positional and attribute information fused at levels which are not necessarily the same. The choice of the fusion level is dependent on the nature and specificity of the information to be fused. For a sensor such as the ESM which is especially devoted to measuring and providing many attributes (all types of emitters), it is synergetically more convenient and appropriate to fuse its information at the level of the emitter declaration instead of at the platform level. A surveillance radar has a very limited capability to observe attributes; the fusion at the contact level could bring more ambiguity and instability. It is thus preferable that the radar processes many contacts in order to get a sufficiently stable attribute declaration. The abstraction level of the radar attribute information is much higher than the abstraction level of the ESM.

In this chapter, points relating the process of target identity and the fusion are described or discussed. These points are: the architecture level of the fusion, the kind of attribute information which may be obtained from the various sensors, the structure of the platform database to which the identity process is applied, and the CCS commander requirements concerning the expected output identity.

3.1 Sensor architecture

Figure 2 below shows how the selected sensors disseminate their information to the fusion box through a specifically tailored communication bus and to the platform Command and Control System (CCS) through the CCS bus. There are many possible interconnection architectures and the one shown in the figure is just one among many.

In this design the MRR, LRR and the IRST send the positional information of their contacts to the positional fusion function (contact level fusion) while the attribute information is fused at the track level. In parallel to this, all sensor track information is sent to the CCS bus which can be considered as the default connection in the absence of fusion or for security redundancy. The selected IFF processes only at the contact level and has its information fused at this level for both kinds of information. The ESM has its information fused at the emitter level. The fusion function collects the sensor information and the results of the fusion are sent to the CCS as any other sensor.

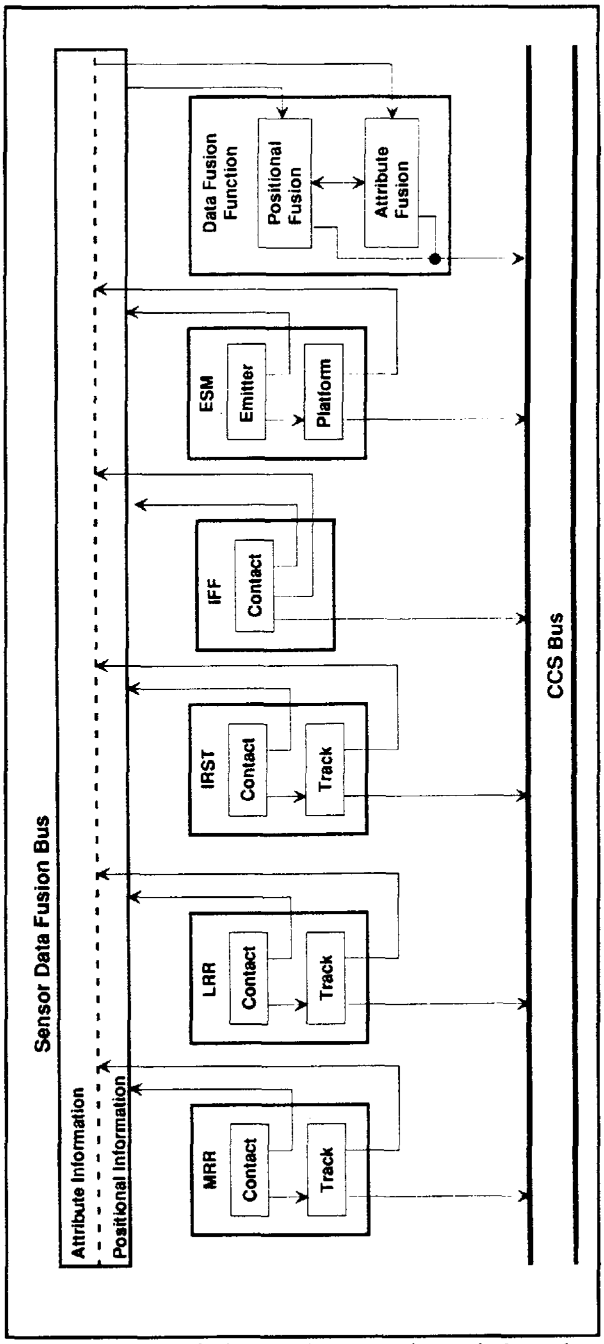

Figure 2 Sensors fusion architecture using an independent and parallel sensor bus for the fusion

3.2 Sensor measurement domain

Table 2 below lists the kind of attribute information which is fused by the multiple sensor fusion function. All the sensors listed in this table are idealized and do not correspond necessarily to existing products. Their capability have been extrapolated according to the current trend of the research and development of the military sensor industries. The MRR is idealized as an advanced naval volume surveillance radar which processes the Doppler effect on the echo returned at the contact level and which detects the modulation of this Doppler effect. The modulation particularity, explained in [Bullard and Dowdy, 1991], allows the MRR to classify or identify the air target class which contains moving parts such as helicopter blades or an aircraft with propellers.

Table 2 Attribute information and level of fusion for each sensor

Sensor	fusion level	Attribute domain	
MRR	track level	air Very large air Large air Medium air small air Very small air helicopter	surface Very large surface Large surface Medium surface Small surface Very small surface air with propeller
LRR	track level	air Very large air Large air Medium air small air Very small air	surface Very large surface Large surface Medium surface Small surface Very small surface
IFF	contact level	Neutral Not answered	friend with code friend without code
IRST	track level	air missile	surface
ESM	emitter level	emitter type (many thousands of members in a typical EDB)	
Positional tracking	track level	Very fast air fast air Med. speed air slow air Very slow air Very large acceleration air large acceleration air medium acceleration air	Very fast surface fast surface Med. speed surface slow surface Very slow surface

The surface and air discrimination is made from the Doppler detection capability. Also, this hypothetical radar outputs an appreciation of the target size through the evaluation of the RCS and the target class. The logic behind the size evaluation is explained in chapter 4. The LRR, as well as the MRR, are capable of detecting the Doppler effect and of estimating the target size but the echo modulation is not processed.

As already mentioned, any radar is in principle capable of outputting the RCS of a contact. Both radars considered in this document evaluate and average over many contacts (track level) the RCS of the targets and associate an attribute to the track using a look-up table. Table 3 shows an example of a look-up table relating the target RCS and an approximative target size attribute declaration for an air and surface (ship platform) target respectively. This information is fused at the track level because, in order for the RCS to be a useful attribute, the target aspect (forward, backward, side) has to be known. The aspect is obtained from the course which is estimated by the radars at the track level.

Using positional information such as the elevation, the cross-range rate and the relative signal intensity between two infra-red wavelength windows, the IRST sensor mentioned in Table 2 is ideally capable of distinguishing an air target from a surface target. The specific sub-class of missile is considered extractable (the missiles have generally a typical and unique infra-red plume).

Table 3 Typical declarations of a radar based on the RCS

Radar RCS Attribute	Interval, AIR in m^2	interval, SURFACE in m^2
very large	RCS $\geq$ 5.0	RCS $\geq$ 50.0
large	2.0 $\leq$ RCS < 5.0	20.0 $\leq$ RCS < 50.0
medium	0.5 $\leq$ RCS < 2.0	5.0 $\leq$ RCS < 20.0
small	0.2 $\leq$ RCS < 0.5	2.0 $\leq$ RCS < 5.0
very small	RCS < 0.2	RCS < 2.0

The attribute domain of the IFF in Table 2 will be considered as relatively simple for this study. For example, depending on the interrogation mode, the domain will have four possibilities: "friendly target with platform code index", "friend without code", "neutral target", and "not answered". If the friendly target answer is obtained, the identification code must be related to a platform identity which exists in the PDB of the fusion function.

The attribute declaration of the ESM sensor will consist of emitters listed in the EDB of the ESM. For maximum efficiency, the PDB must be aware of all the emitters listed in the ESM EDB.

The target tracking process of the positional fusion function contains information from which some attributes may be attached to the tracked target. As an example, if the target speed is estimated to be 1200 Dm/hr (mach 1.9), there is a strong indication that this target is an air target with a maximal speed higher than or at least equal to 1200 Dm/hr. With the use of an algorithm comparing the speed before and after a manoeuvre it is also possible also to get an attribute information about the target acceleration capability of an air target. For air targets the acceleration is usually appraised in units of g (gravity acceleration). The last row of Table 2 lists all the attributes which may be extracted by an attribute extractor algorithm within the positional fusion function. The target speed attribute is obtained by comparing the estimated speed to a look-up table as shown in table 4. The acceleration (g-turn capability) attribute is obtained similarly and is shown in Table 5.

Table 4 Typical speed attribute declaration from the positional fusion process

Speed attribute	Speed interval, AIR in Dm/hr	Speed interval, SURFACE in Dm/hr
very fast	speed $\geq$ 1000	speed $\geq$ 40
fast	600 $\leq$ speed <1000	30 $\leq$ speed < 40
medium	300 $\leq$ speed < 600	20 $\leq$ speed < 30
slow	100 $\leq$ speed < 300	10 $\leq$ speed < 20
very slow	speed < 100	speed < 10

Table 5 Typical acceleration attribute declaration from the positional fusion process

g-turn attribute	acceleration interval (air only) in m/s^2
very large	acceleration $\geq$ 50
large	20 $\leq$ acceleration < 50
medium	acceleration < 20

In both tables the numbers defining the speed and acceleration attributes are, for the moment, tentative and for the purpose of this study. Only three attributes are used for the acceleration. This attribute is particularly useful for target discrimination of highly manoeuvring targets, when large accelerations are detected.

3.3 Platform database

The Dempster-Shafer evidential method is applied over a set of propositions called a frame of reference. This set is in fact the Platform Data Base (PDB) which contains all the "values" that the variable "platform identity" may take. Each record of this data base contains information related to the measured sensor attributes. Table 6 below shows the field structure of a record. Eleven fields are used to describe the platform characteristics. Two fields, the first and the third, are used by the track management function of the fusion algorithm and contain information not measured or estimated by the sensors. The other fields are directly or indirectly connected to the attribute domain shown in Table 2.

The first field is a number index; a typical platform data base may have many thousands of entries. The second field is the platform identity. It is possible to assign only a generic class identity as in the case of a commercial aircraft, merchant ship or pleasure ship. For such a generic class the attribution of a specific attribute such as the RCS may vary a lot. The third field represents the threat level. It is used to give priority to the processing, especially when the fusion function is overloaded.

The fourth field, the allegiance, refers to attribute information provided by the IFF. It is different from the threat level in the sense that the allegiance is related to the intention of the commanding crew of the platform. For platforms such as commercial aircraft or merchant ships the allegiance is considered as neutral. The allegiance concept is not applicable to the missiles because those platforms are subordinated to other platforms which have their own allegiance.

The fifth field indicates the target type, air or surface. It may be determined by the LRR, the MRR and the IRST or the positional fusion. The sixth field is a sub-product of the air type target. It indicates the air class attributes as measured by the MRR for helicopters or aircraft with propeller and by IRST for missiles. This field is not applicable to a surface target. Since the commercial aircrafts are entered in the PDB as a generic class, their values should be considered as "various". This applies also for the RCS, speed and acceleration fields.

Fields 7 and 8 correspond to the RCS of the target as measured by both radars for the forward and side target aspects respectively. This information does not exist in the current threat data bases. The advent of fusion which permits the use of highly ambiguous attribute information from sensors not particularly devoted to identify targets will oblige the military community to rethink the actual threat data base and include some information such as those of fields 7 to 10. The information contained in fields 9 and 10 is related to the dynamics of the target and is measured by the positional fusion algorithm. The acceleration is only for an air target and does not apply to a surface target. Finally, field 11 lists all the emitters of the platforms which could be detected by the ESM sensor. To determine emitter composition, an ESM utilizes an Emitter Data Base (EDB). Therefore, instead of listing the emitter identity, the PDB has to list only the entry index number to the EDB.

Table 6 Structure of a PDB used for target identity estimation

Field content	Comment
Index	Record number. Used for track management.
Platform identity	Country and Platform name. This attribute can be measured by the IFF.
Threat level: Very high threat, high threat, medium, harmless	Not measured by the sensors. Used for track management.
Allegiance: Friend, foe, neutral, N/A	Measured by the IFF sensor.
Type: Air, surface	Measured by the LRR, MRR and the IRST and the positional fusion.
Class (air): Missile, helicopter, aircraft with propeller, N/A, various	Measured by the MRR and the IRST.
RCS forward: Very large, large, medium, small, very small, various	Forward aspect of the RCS measured by the radar.
RCS side: Very large, large, medium, small, very small, various	Side aspect of the RCS measured by the radar.
speed: Very fast, fast, medium, slow, very slow, various	Attribute estimated by the positional fusion function.
g-turn: Very large, large, medium, N/A, various	Attribute estimated by the positional fusion function.
Emitters: List of indexes to the ESM EDB	Emitters detectable by the ESM that belong to this platform.

3.4 The desired solutions

From the point-of-view of a CCS commander of a patrol ship platform, the goal of estimating the identity of a target using sensor measurements and sophisticated algorithms is to get a unique and unambiguous answer to the question "who is this target?". If the answer is extractable it would be desired that this answer be only one platform identity amongst the many members of the PDB. Unfortunately, such a clear and categoric answer is rarely reached and the commander has to deal with a list of identities or sometimes a generic class of target. This is due to the ineptitude of the sensors to measure all the distinctive attributes of a target which uniquely characterize this target. Instead, the sensors measure incomplete sets of data which correspond to a group of identities. This group is named a non-exclusive or generic proposition.

Dempster-Shafer evidential theory is capable of handling and combining non-exclusive propositions. During the combination process other propositions which come from the conjunction of the sensor propositions are created. In real life if a commander cannot get a single exclusive identity he will prefer to rely on a list of the most probable exclusive identities, such as the identity is "CF-18 with 12% confidence", "USAF F-18 with 10%", "USN F-14 with 6%". This will be preferred to a non-exclusive proposition such as the identity is "CF-18 or USAF F-18 or USN F-14, with 30% confidence" and to a negative proposition as the identity is "not helicopter class". These exclusive propositions are named candidate identity propositions.

The commander will accept some generic propositions only if they represent a class of targets sharing an attribute which presents a tactical interest, such as "the target is a friend, with a confidence of 65%" or "Canadian platform with 45%". These non-exclusive propositions will be called generic propositions. They are non-exclusive because a proposition such as "friend" is a subset of the PDB which contains many elements. All the elements of this subset share the same attribute, i.e., they have the friend flag opened in the allegiance field as shown in Table 6.

Table 7 below lists some typical generic propositions that an attribute data fusion should try to estimate and output to the operator in addition to the specific propositions. Here only 15 have been selected but in general they could be more numerous and dependent on the mission.

Table 7 Example of generic propositions that must be evaluated by the attribute fusion function

not friend	other country	surface
neutral	helicopter	very high threat
friend	missile	high threat
Canadian	attack aircraft	medium threat
US	air	harmless threat

Each of these 15 propositions is a subset of the PDB which represents the frame of discernment in the Dempster-Shafer jargon. If the frame of discernment contains 2500 elements there is a myriad of generic identities which can be formed. Most of them have no tactical or strategic interest. If a Dempster-Shafer evidential algorithm runs during a very long period of time (regardless of the processing power and memory), receiving and combining periodically various input attributes, it will create and assess a tremendous amount of these non-exclusive propositions. Any implementation of a Dempster-Shafer evidential algorithm should control the calculation of the combined propositions. This problem is addressed in the next two chapters.

The last kind of proposition is the ignorance, symbolized by Θ. This is a sub-product of the evidential approach and it corresponds to the frame of reference. When the Dempster-Shafer evidential approach is applied, the frame of reference proposition, i.e. any identity of the PDB, usually has a non-zero belief value. The size of the belief in the frame of reference proposition is important for the commander. A large belief is an indication that the identity estimator process needs more sensor evidence.

4 Fusion using Dempster-Shafer

The Dempster-Shafer theory of evidence has been identified recently as a powerful approach to manage the uncertainties within the problem of target identity [Garvey, Lowrance and Fischler, 1981; Garvey and Lowrance, 1983]. As various evidences are combined over time, Dempster-Shafer combination rules will have a tendency to generate more and more propositions which in turn will have to be combined with new input evidences. This problem is known to increase exponentially (for a complete review of Dempster-Shafer evidential theory see [Shafer, 1982; Strat, 1984; Hall, 1992]). The algorithm which is proposed here rigorously controls the amount of input and output propositions. In this chapter a modification of the usual Dempster-Shafer algorithm is proposed.

4.1 Truncated version of Dempster-Shafer

Figure 3 describes the main steps of this algorithm. The computation performed by this identity estimator is divided into 4 sub-functions. After reception of the sensor declarations the first task is to build the sensor propositions. The sensor proposition construction subroutine translates each sensor declaration into subsets of the PDB and computes a confidence level for each subset. This process is explained in section 4.2.

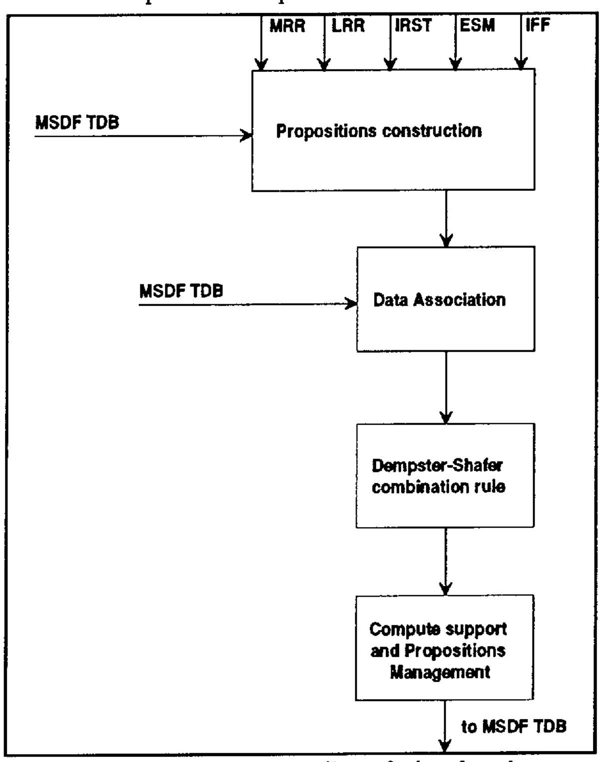

Figure 3 Multiple sensors attribute fusion function

The second task is the data association process. This process determines to which MSDF track the received sensor information belongs. This is the most critical process of any fusion function. For the moment the algorithm proposed in this chapter will be applied to a single target scenario where the data association is trivial.

Following the conclusions of the data association process the Dempster-Shafer combining rules are applied to fuse the data fusion target identity propositions list with the sensor propositions. It is at this level that beliefs are calculated and new propositions may be obtained from the combination rules. The results of the combination are sent to the output proposition management subroutine which is responsible for pruning the "unessential" propositions, selecting the "best" identity propositions and computing the support of the generic propositions. As shown in Figure 3, the MSDF Tracks Data Base (TDB) are also part of the input parameters for the proposition construction and data association processes.

4.2 Input proposition preparation

The proposition construction subroutine receives data from the sensors on a continuous basis. These declarations are given into the format of the sensors. The proposition construction subroutine has to accomplish two tasks. First, the algorithm must be capable of transforming the format of the sensor declaration into the format of the PDB which will be fused subsequently. Secondly, the algorithm must evaluate the belief (basic assignment probability) for each declaration.

When excluding the IFF "friend with code ..." and the ESM declarations, Table 2 shows that the fusion function may receive up to 41 different declarations. The number of IFF "friend with code ..." declarations is equal to the number of friend platforms in the PDB and the number of ESM declarations is related to the number of emitters in the EDB and the complexity of the ESM declarations. As an example, the ESM is capable of declaring a proposition which includes a logical operator such as "target has emitters x and y" and may be as complex as "target has emitters (x and y) or (x and z) and not (x and y and z)". In such a circumstance the proposition construction subroutine must be capable of dealing with the complex ESM declarations.

In this study, a special logic has been used with the IFF declaration. When the IFF does not obtain an answer from an interrogation, the subroutine could presume that the proposition to be processed is the set of "not friend" platforms with a somewhat large value of belief, the rest of the belief being associated to the ignorance. Such a logic does not consider that when a target does not answer it is probably a commercial target or a friend target having reception problems. Therefore, in addition the propositions "commercial" and "friend" should be considered with a belief value lower than the one associated to "not friend". Moreover, the particularity of evidential reasoning permits that a belief may still be assigned to the ignorance proposition Θ, in spite of the fact that the three propositions friend, not friend and neutral target together represent the set Θ. As an example, the IFF declaration at times 2,3, and 9 in Table 9 includes such sophistication in the declaration treatment.

Another place where refinement in the declaration may be applied is when the radar declares the size of the target RCS. The RCS is a quantity which may fluctuate strongly as a function of time. In general, the proposition construction subroutine will assign a small amount of belief to the proposition set corresponding to the declared RCS size while a large portion of the belief will be given to the ignorance. Since the measure of the target RCS is imprecise, the subroutine could refine the proposition construction in distributing some of the belief to the RCS classes just above and under the declared one.

The proposition construction subroutine must also calculate the uncertainty (confidence level) of the sensor declarations. Since Dempster-Shafer evidential theory is used here, the uncertainty is expressed by an evidential belief. Therefore, in some circumstances, it is possible that the subroutine gives a non-zero belief to some other propositions which represent the negation of the assessed propositions (this happens for the IFF declaration).

The computation of the belief relies on the declaring sensor and is a function of many parameters. If the declaration is from a radar and concerns the RCS, the belief may be a function of the signal-to-noise ratio of the contacts, the knowledge of the aspect from the course value, the radar environmental conditions, the target density, the range of the contacts, etc. When dealing with the fusion of attribute information, one has to consider that most of the time the declarations are subjective and consequently their confidence level is inherently imprecise. It is thus irrelevant to develop rigorous expressions; the fusion function may be performed with confidence level expressions which are, for each parameter, phenomenologically in agreement with the expected behaviour.

As it will be see in the last column of Table 9 the belief attribution does not follow a particular equation or process. The attribution was dictated by common sense. The development of exact equations for all types of sensors, except to a certain level for a radar, has not yet been achieved in the literature. This task is very complex and should be part of a separate research project.

4.3 Belief combination rules

The created propositions are sent to the subroutine which applies the Dempster-Shafer rules of belief combination. This subroutine combines the new proposition with the retained propositions of the previous run (or scan). The algorithm is time sequential, it combines the sensor propositions SP_j, declared at a time $t+\Delta t$, with the fused propositions FP_i, estimated at the time t, to get a new estimated set of fused proposition FP_k. The belief of the new estimated propositions are obtained from Dempster's rule of combination:

$$b(FP_k) = \sum_i \sum_j \frac{b(FP_i)\, b(SP_j)}{1 - Conflict_k} \qquad (1)$$

$$where \qquad FP_i \cap SP_j = FP_k$$

where $Conflict_k$ is the conflict between the combined propositions at time t+Δt.

$$Conflict_k = \sum_i \sum_j b(FP_i)\, b(SP_j) \qquad \textbf{(2)}$$
$$where \qquad FP_i \cap SP_j = \varnothing$$

The summations, over the indexes i and j, are restricted to the propositions FP_i and SP_j such that the intercept between these propositions is equal to the proposition FP_k and the empty set respectively.

4.4 Output proposition preparation

Since the combination rules create many new propositions at an exponential rate, the number of retained solutions must be limited. It is the role of the output proposition management subroutine to apply selection criteria that control the population of the fused propositions. The management proposition subroutine performs three fundamental kinds of calculation:

i) computes the evidential support of a specific set of generic proposition,

ii) applies selection criteria to save a limited amount of solution identity propositions, and

iii) computes the belief associated to the ignorance.

The evidential support of a generic proposition GP is computed from the sum of the beliefs of all the propositions FP_k which are subsets of GP:

$$spt(GP) = \sum_{FP_k \subset GP} b(FP_k) \qquad \textbf{(3)}$$

In order to save processing time the evidential plausibility is not computed. The summation implied by the plausibility contains more terms than the summation needed for the support.

The identity propositions are retained according to the following criteria:

i) All propositions FP_i which have a belief higher than MaxBe are retained.

ii) All propositions FP_i which have a belief lower than MinBe are eliminated.

iii) If the number of retained propositions in step "i" is smaller than MaxNum, the subroutine will retain, by decreasing belief, the propositions consisting of one element (platform) until MaxNum is reached. If MaxNum is not reached, the subroutine retains, by decreasing belief, the propositions consisting of two elements. The process is repeated until MaxNum is reached.

At the end of this process the evidential support of all the retained propositions is computed using an expression which is similar to equation (3).

The belief in the ignorance or frame of discernment Θ must not be computed using equation (1). The parameters MinBe and MaxNum have been used to eliminate a portion of the belief which belongs to some dropped propositions. The most crucial approximation of this Dempster-Shafer algorithm is made here. The belief of the dropped propositions will be assigned to the ignorance, such that:

$$b(\Theta) = 1 - \sum_{i=1}^{MaxNum} b(FP_i) \qquad \textbf{(4)}$$

where the summation is only over the retained propositions.

The two approximations associated to the parameters MinBe and MaxNum lead to two great advantages. They control the population of the processed propositions and ensure adaptivity in case of contradiction between new sensor declaration SP_i and the previous retained solution FP_j.

5 Application

5.1 Example of a PDB and a Test Scenario

To apply an identity estimator algorithm a PDB and sensor declarations are necessary. For that purpose, a very small PDB made of 16 elements has been constructed and a test scenario where sensors report information on a single detected target has been designed. The PDB is presented in Table 8. The information given in this table is mostly true and extracted from Jane's [Lambert, 1991; Moore, 1987]. Some details have been modified and added for the purpose of the study in order to produce redundancy. This redundancy is needed to evaluate the efficiency of the input proposition construction subroutine. Concerning the RCS data, a guess based on the target size has been used due to the absence of this information in the open literature. The allegiance has been arbitrarily given only for the purpose of this study and is not related to any political or military situation. An N/A entry refers to an attribute being not applicable for a certain platform.

Table 8 PDB used to evaluate the identity estimator algorithms of this study

Index	Identity	threat level	allegiance	type	class	RCS forward	RCS side	max. speed	Accelera-tion	Emitter
1	Canada, coastal surveillance, CP-140A	Harmless	friend	air	propeller	large	very large	medium	medium	APX-134, APN-510
2	Canada, training, CT-142	medium	friend	air	propeller	large	large	slow	medium	APN-128D
3	Canada, attack aircraft, CF-18A	high	friend	air	N/A	small	medium	very fast	very large	APG-65
4	Canada, attack aircraft, CF-105	high	friend	air	N/A	small	medium	fast	large	APG-65
5	Canada, ASW helicopter, EHI-101	high	friend	air	helo	medium	very large	medium	medium	APN-510
6	Tomahawk BMG-109	very high	N/A	air	missile	very small	very small	medium	very large	DSQ-28
7	Harpoon RGM-84A	very high	N/A	air	missile	very small	small	medium	very large	DSQ-28
8	Exocet MM 38/40	very high	N/A	air	missile	very small	small	fast	medium	ADAC
9	US Navy, ASW, S-3	medium	foe	air	N/A	medium	large	fast	medium	APX-137
10	USAF, bomber, B-52	high	foe	air	propeller	very large	very large	medium	medium	APX-134
11	Canada, Destroyer, Halifax class	high	friend	surface	N/A	medium	large	fast	N/A	SPS-49, SG-150, Mk-340, STIR VM 25
12	Canada, Destroyer, Trump class	high	friend	surface	N/A	medium	large	medium	N/A	SPS-509, SPQ 2D, MK-60
13	Denmark, frigate, Nieals Juel class	medium	neutral	surface	N/A	small	medium	medium	N/A	Plessey AWS 5, SG-150,
14	US Navy, Aircraft carrier, Nimitz class	very high	foe	surface	N/A	large	very large	very fast	N/A	SPS-48, SPS-49, SPS-64, SPS-67, SPN-41, SPN-42, SPN-43, SPN-44
15	commercial air	harmless	neutral	air	various	various	various	various	various	commercial
16	merchant ship	harmless	neutral	surface	N/A	various	various	various	N/A	commercial

The test scenario is sketched in Figure 4 and the reported sensor declarations are listed in Table 9. In this scenario an Aurora CP-140A aircraft is passing in the horizon of the ownship at a velocity of 450 DM/hr in the southern direction. The point of closest approach is 75 Dm. Between 12:00 and 13:00, 21 sensor declarations have been selected to be fused. The target range when the first declaration is sent at 12:00 is 290 Dm and only the LRR is capable of tracking at such a distance.

Table 9 lists only the sensor declarations which have been retained by the proposition construction subroutine. The study considers that the sensors do not report negation declaration as "not missile class". Also, in other to test the capability of the identity estimator algorithm to deal with contradictions, some very bad declarations have been introduced, such as at times 2 and 4 concerning the target RCS.

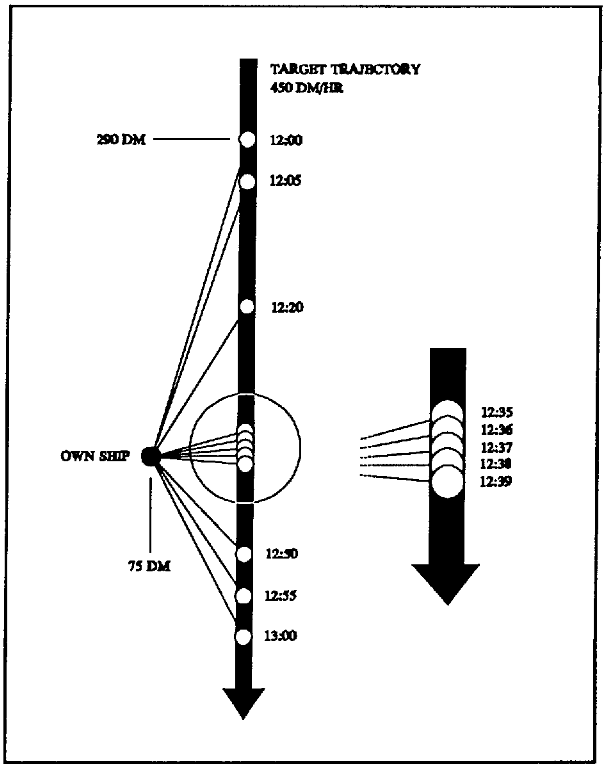

Figure 4 Test scenario showing an air target with 11 declaration times

Table 9 List of the scenario sensor declarations used as input for the identity estimator function

time		Sensor	Declaration	Constructed propositions	Confidence
1	12:00	LRR LRR Pos. DF Pos. DF	air large RCS forward air medium speed	{1,2...10,15}, Θ {1,2,15}, {10,15}, {5,9,15}, Θ {1,2...10,15}, Θ {1,3...10,15}, Θ	0.55, 0.45 0.20, 0.10, 0.10, 0.60 0.65, 0.35 0.50, 0.50
2	12:05	LRR LRR IFF mode 4	air medium RCS forward no answer	{1,2...10,15}, Θ {5,9,15}, {1,2,15}, {3,4,15}, Θ {6...10,14}, {1...5,11,12}, {13,15,16}, Θ	0.95, 0.05 0.20, 0.10, 0.10, 0.60 0.30, 0.10, 0.30, 0.30
3	12:20	IFF mode 4 Pos. DF Pos. DF	friend no code air medium speed	{6...10,14}, {1...5,11,12}, {13,15,16}, Θ {1,2...10,15}, Θ {1,3...10,15}, Θ	0.05, 0.90, 0, 0.05 0.95, 0.05 0.95, 0.05
4	12:35	LRR	large RCS side	{2,9,15}, {1,5,10,15}, {3,4,15}, Θ	0.30, 0.15, 0.15, 0.40
5	12:36	MRR ESM	propeller APX-134 or DSQ-28	{1,2,10,15}, Θ {1,6,7,10},Θ	0.70, 0.30 0.60, 0.40
6	12:37	MRR	very large RCS side	{1,5,10,15}, {2,9,15}, Θ	0.50, 0.17, 0.33
7	12:38	LRR	very large RCS side	{1,5,10,15}, {2,9,15}, Θ	0.50, 0.17, 0.33
8	12:39	MRR MRR IRST	very large RCS side propeller air	{1,5,10,15}, {2,9,15}, Θ {1,2,10,15}, Θ {1,2...10,15}, Θ	0.65, 0.12, 0.23 0.90, 0.10 0.95, 0.05
9	12:50	IFF mode 4	friend no code	{6...10,14}, {1...5,11,12}, {13,15,16}, Θ	0.05, 0.90, 0, 0.05
10	12:55	ESM	APX-134 or APX-137	{1,9,10}, Θ	0.90, 0.10
11	13:00	ESM	APN-510	{1,5}, Θ	0.90, 0.10

5.2 Results

This approximated Dempster-Shafer algorithm has been applied to the scenario sketched in Figure 4 with the sensor declarations listed in Table 9. The algorithm parameters were tentatively set to MinBe = 0.01, MaxBe = 0.10 and MaxNum = 8. The resulting generic propositions, identity proposition and ignorance are listed in the next pages.

At the first time, 6 sensor declarations are fused. At this moment only 6 resulting fused propositions are generated and there is no need to apply approximation and selection criteria. As time evolves more propositions are created and selection criteria have to be applied. Since the criteria withdraws propositions with relatively large beliefs (less than 0,10) the resulting ignorance becomes larger than would have been expected using the exact Dempster-Shafer formulation. As an example, at time 5, table 10 shows a value of 0.0546 compared to 2.0 X 10^{-8} without the application of the selection criteria. Some propositions with relatively high belief have been withdrawn because the criteria favour the propositions having few elements.

At time 5, when the MRR sensor declares the presence of an aircraft with propeller, this immediately favours the proposition {1}. This proposition remains the best identity candidate until the end of the scenario. Figure 5 compares the belief obtained by the exact Dempster-Shafer evidential theory with the approximate version, for the proposition {1} and the ignorance. The horizontal scale show the 21 fusion scans and the equivalent scenario times. The dashed curve shows the ignorance as calculated by the truncated version. The ignorance for the exact formulation becomes practically zero after the fifth scan. As expected, the approximate version provides results for {1} which are smaller or equal to the exact formulation but this observation does not hold all the time for all proposition. Some propositions such as {1,3,4,5} at time 5 were found to have a belief and a support larger than the exact formulation. Except for the ignorance, most propositions of the approximated formulation have an combined belief close to the belief obtained with the exact formulation. The biggest difference is naturally on Θ, which stays close to zero after the first run with the exact formulation. Some result of the exact formulation of Dempster-Shafer evidential theory are listed in the table 9 below. The fusion of all the sensor retained propositions from time 1 to time 5 is performed and this leads to 32 propositions. The 8 most important ones (higher belief) are listed.

Table 10 8 best propositions obtained by the exact fusion of declarations from times 1 to 5

propositions	belief	propositions	belief
{1}	0.7010	{5}	0.0325
{15}	0.0625	{3,4}	0.0257
{10}	0.0589	{1,5}	0.0159
{1,3,4,5}	0.0414	{1,10}	0.0094

The proposition management subroutine of the truncated version is applied at each fusion scan and selects the best 8 propositions according to the three criteria explained in section 4.3. The results listed for the times 1, 3, 5, 7, 9 and 11 are listed in the table 11. As may be seen the outputted propositions are in relative agreement with the exact formulation concerning the most important one. In fact the resulting belief of the truncated version has a discrepancy which is of the order of the belief of Θ obtained at the previous scan, which is the theoretical limit of the method.

Table 12 lists the support obtained by five generic propositions as computed by the truncated version algorithm. The data are compatible with the attribute of the simulated target (CP-140A) and are also close to those obtained with an exact formulation. Those generic propositions request a lot of processing to be computed and without the selection criteria the exact calculation would have spoiled the real-time processing requirement.

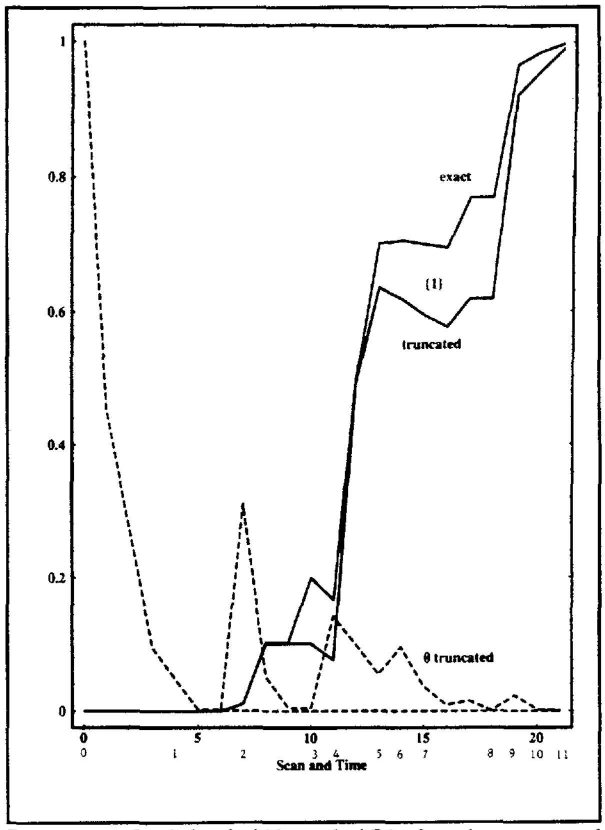

Figure 5 Belief of {1} and {Θ} for the truncated Dempster-Shafer compared to the exact formalism

Some contradictory sensor declarations have been voluntarily included in the scenario at time 2 and time 4. The radar RCS and IFF declarations listed in table 9 are not compatible with the simulated target platform, the CP-140A, described in the PDB (table 8). At time 4 the contradiction has practically no effect on the result. At time 2 some platforms such as {9} get a belief larger than the true answer {1}. These contradictions were included for the purpose of testing the estimator robustness and ability to recover on the right identity. These contradictions explain the chaotic behaviour observed in the beginning of the curves in figure 5. This contradiction happens at the beginning of the process where many multiple-element propositions exist, the combination of evidence at time 3 still has the capability to reorient the belief on some more compatible solutions. If some contradicting declarations would have been fused later in the process the recovering would have been more complicated for the exact Dempster-Shafer.Usually, when an exact Dempster-Shafer algorithm puts a large belief on a wrong proposition (due to counter-measure or systematic error) and the belief in the ignorance is very small (this happens at the end of the process), it will take a lot of declarations to reorient the algorithm on the correct proposition. An approximate Dempster-Shafer such as the one proposed in this chapter has the great advantage of keeping the ignorance large enough to make the recovery easier and faster.

Table 11 Belief and support of the selected candidate identity proposition at the end of some fusion time

Time 1			Time 3			Time 5		
proposition	belief	support	proposition	belief	support	proposition	belief	support
{1,3...10,15}	0.3000	0.6000	{1,3,4,5}	0.6333	0.7861	{1}	0.6350	0.6350
{1,2,...10,15}	0.2528	0.9528	{1}	0.1006	0.1006	{15}	0.0321	0.0321
{1,15}	0.1000	0.1000	{5}	0.0523	0.0523	{10}	0.0169	0.0169
{10,15}	0.1000	0.1000	{15}	0.0462	0.0462	{1,10}	0.0748	0.7267
{5,9,15}	0.1000	0.1000	{9}	0.0165	0.0165	{1,5}	0.0208	0.6617
{1,2,15}	0.1000	0.2000	{6,7,8,9,10}	0.0648	0.0813	{1,6,7,10}	0.0632	0.7899
			{1,2,3,4,5}	0.0317	0.8178	{1,3,4,5}	0.0527	0.7145
			{1,3,...10,15}	0.0503	0.9640	{1,2,10,15}	0.0499	0.8087
Ignorance Θ	0.0472	1	Ignorance Θ	0.0043	1	Ignorance Θ	0.0546	1
Time 7			**Time 9**			**Time 11**		
proposition	belief	support	proposition	belief	support	proposition	belief	support
{1}	0.5938	0.5938	{1}	0.9212	0.9212	{1}	0.9898	0.9898
{1,10}	0.1055	0.7150	{10}	0.0156	0.0156			
{15}	0.0611	0.0611	{2}	0.0133	0.0133			
{10}	0.0158	0.0158	{1,5}	0.0114	0.9326			
{1,5}	0.0490	0.6428	{1,2,3,4,5}	0.0155	0.9614			
{1,10,15}	0.0280	0.8041						
{2,9,15}	0.0245	0.0855						
{1,5,10,15}	0.0857	0.9388						
Ignorance Θ	0.0367	1	Ignorance Θ	0.0230	1	Ignorance Θ	0.0102	1

Table 12 Support of some generic proposition as function of time

proposition	1	2	3	4	5	6	7	8	9	10	11
air	.9528	.9984	.9981	.9976	.9579	.9787	.9633	.9992	.9991	.9977	.9956
Canadian	.0000	.0945	.8194	.7695	.7145	.6897	.6428	.6186	.9622	.9609	.9919
US	.0000	.0899	.0165	.0561	.0233	.0164	.0158	.0153	.0156	.0158	.0016
helicopter	.0000	.0230	.0523	.0396	.0060	.0000	.0000	.0000	.0000	.0000	.0000
harmless threat	.1000	.4327	.1468	.1397	.6671	.6556	.6549	.7177	.9269	.9568	.9898

5.3 Data association

For multiple targets or high clutter situation there is no formal contact-to-track formalism which have been rigorously developed for the evidential theory as it is the case with the Bayesian probabilistic formalism. This subject is under investigation. It have been observed [Garvey and Lowrance, 1983] that it appears reasonable to use the conflict (calculated by expression (2)) between the combination of the sensors declaration and the proposed list of identities in the track as a selection criteria.

5.4 Relative comparison between the exact and the truncated formalism

During the application to the simple scenario many observations have been made about the general performance of the fusion algorithm described above. Without an explicit mention in the previous section, all the observations have been grouped in table 13. Nine performance criteria related to the quality of the fusion, the complexity of the design and the Operator Machine Interface (OMI) aspect have been retained. The performances are gauged and indicated using 3 attributes: good, acceptable and poor. Based on the previous experience of Paramax in the integration of military platforms, the first four criteria are the most critical.

The truncated Dempster-Shafer performs the best due to its performance on the most critical criteria. The results are preliminary and just indicative. A research study where the algorithms are applied on various scenarios and a bigger PDB are necessary to validate the performance evaluation.

Table 13 Performance comparison between the exact and truncated versions of the evidential theory

criteria	Truncated	Exact
Processing requirements	good	poor
Derivation of identity candidate	acceptable	good
Calculation of generic proposition	good	acceptable
Operator machine interface	good	poor
Data base requirements	acceptable	acceptable
Flexibility to deal with sensor contradictions	good	poor
Software design complexity	good	acceptable
Assessment of target not in the PDB	poor	poor
Data association	good	good

6 Application to CPF

The truncated version of the Dempster-Shafer algorithm has been selected as the most appropriate for the implementation of the MSDF system demonstration model within the real-time CCS environment of the CSTSF at Paramax.

The CSTSF consists of two subsystems: (a) operations system, which is a full scale Combat System (CS), and (b) simulation system, which stimulates the environmental, target and weapon information. Both the operations system and the simulation system have distributed computer architecture, consisting of a number of computers communicating via a serial data bus. The MSDF system demonstration model is currently being implemented to function in the operations system, connected to the operations bus, within the threat and the environment provided by the simulation System. Figure 6 shows the MSDF processor within the distributed computer architecture of the CSTSF operations and simulation systems. This processor is selected to be a SUN SPARC 10 workstation, trapping all messages on the operation bus, and performing its fusion processing without any modifications to the CPF configuration, guaranteeing that the performance changes are only due to the incorporation of MSDF.

The MSDF processor maintains a copy of the CPF CCS database for tracking and identification, builds its own MSDF database of target state and identity from the same sensor data trapped from the operations bus, which was used by CPF CCS to establish its database. This data is used by the Performance Evaluation function within this system that compares the CPF CCS and MSDF system's target state and identity estimation performance.

As this is the first time an MSDF capability is being implemented within the CPF CCS, it is clear that a few iterations may be necessary before optimal fusion algorithms are selected for CPF using the CSTSF facility. Therefore the discussion of the attribute information used in the truncated version of the Dempster-Shafer algorithm being implemented in this system should be viewed as an example of how some of the attribute information available on CPF, specifically the data from ESM and IFF can be fused using these techniques. The typical attribute information fused are the target speed from the positional data fusion, the target type from the radars and IFF, the target allegiance from the IFF, the emitter composition from the ESM (simulated from a list extracted from Jane's). The PDB is built from Jane's and excludes acceleration and RCS. Table 14 shows the attribute information and level of fusion performed for the CSTSF sensors.

Table 14 Attribute information and level of fusion for CSTSF simulated sensors

Sensor	fusion level	Attribute domain	
MRR SG-150	track level	air	surface
LRR AN/SPS-49	track level	air	surface
IFF	contact level	neutral not answered	friend with code friend without code
ESM	emitter level	emitter type (typical EDB for simulation created from Jane's)	
Positional tracking	track level	very fast air fast air med. speed air slow air very slow air	very fast surface fast surface med. speed surf. slow surface very slow surface

The attribute data shown in table 14 is not the only information available in CSTSF for use in the Dempster-Shafer algorithms. Examples of other data could be the acceleration from state estimation, data from the CIO senor and data from other platforms received via Link. In the current implementation only a subset data is being used to keep the initial implementation simple. Once the initial algorithms are developed and their identification performance has been evaluated, the incorporation of additional information and the evaluation of the effectiveness of the additional data can be the next step of investigations.

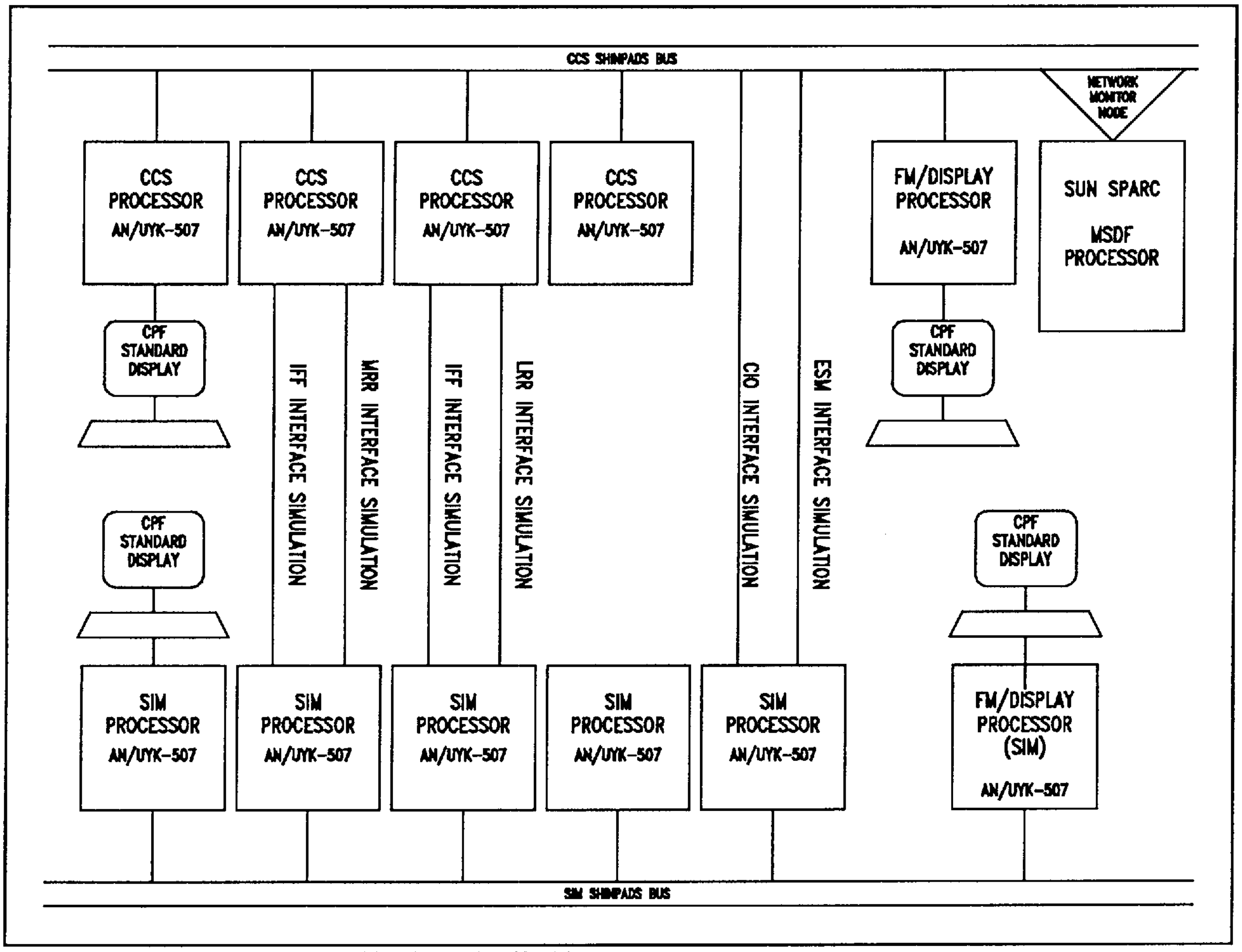

Figure 6 The CSTSF MSDF Simulation Facility

Acknowledgements

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References list

Bar-Shalom Y., 1990; Multitarget-Multisensor Tracking: Advanced Applications, Artech house, Boston.

Bar-Shalom Y., 1992; Multitarget-Multisensor Tracking: Applications and Advances, Volume II, Artech house, Boston.

Bégin F., Simard M.-A. and Valin P., 1993; Contact Level Fusion of Radar and IRST Contacts on Almost Electromagnetically Silent Platform, presented at the 57th NATO AGARD Guidance and Control Panel symposium on Pointing and Tracking Systems, Seattle USA, 12-15 October 1993.

Bullard B.D. and Dowdy P.C., 1991; Pulse Doppler Signature of a Rotary-Wing Aircraft, IEEE AES Systems Magazine, May 1991, PP 28-30.

Delong P.R., 1992; Painting the Battle Group's Tactical Picture, Proceedings, June 1992, PP 87-90.

DREO EWCP, 1992; Integration of Electronic Warfare assets on Maritime Platforms - Phase I, Request for Proposal, SSC File No. 027ST.W7714-2-9616/A. See also New Naval Electronic Warfare Integrating EW and C^2, International Defense Review 7/1992, PP 649-650.

Garvey T.D. and Lowrance J.D., 1983; An Implementation for Multi-Sensor Integration, Appendix A of Machine Intelligence for Electronic Warfare Applications, Report No. AFWAL-TR-83-1168 and AD-B080177, November 83, SRI Menlo Park, CA.

Garvey T.D., Lowrance J.D. and Fischler M., 1981; An Inference Technique for Integrating Knowledge for Disparate Sources, Proc. 7th Int. Joint Conf. Artificial Intelligence, Univ. of British Columbia, Vancouver BC, pp 319-325.

Hall D., 1992; Mathematical Techniques in Multisensor Data Fusion, Artech House Inc, Norwood MA.

Lambert M., 1991; Jane's all the world's aircraft, Edited by Mark Lambert, Jane's Information Group, London.

Moore J., 1987; Jane's fighting ships, Edited by Capt. John Moore, Jane's Information Group, London.

Nahin P. and Pokoski J., 1980; NCTR Plus Sensor Fusion Equals IFFN or Can Two Plus Two Equal Five?; IEEE Trans. On Aerospace & Electronic Systems, Vol.Aes-16, No.3.

Poinsett B.F. and Schmiedeskamp J.E., 1988; NATO AAW Weapon System (NAAWS) IFF Integration concept study, Fleet Systems Department, Johns Hopkins University, Laurel MD.

Royal Navy EWCP, 1992; Improved EW on the Horizon, Jane's Defence Weekly, 15 August 1992, PP 35.

Schleher D.C., 1986; Introduction to Electronic Warfare, Artech House Inc, Norwood MA.

Scott W.B., 1992; New F/A-18C/D Software to Integrate Sensor Inputs, Reduce Pilot Workload, Aviation Week and Space Technology, February 1992, PP 46-47.

Shafer G., 1982; Belief Functions and Parametric Models, Jour. of the Royal Statistical Society, Vol. B-44, pp 322-352.

Strat T.M., 1984; Continuous Belief Functions for Evidential Reasoning, Proc. of the American Association for Artificial Intelligence, pp 308-313.

Stimson G.W., 1983; Introduction to Airborne Radar, Published by Hughes Aircraft Company, Radar Systems Group, El Segundo CA.

Waltz E. and Llinas J., 1990; Multisensor Data Fusion, Artech House Inc, Norwood MA.

Waltz E.L. and Buede D.M., 1986; "Data Fusion and Decision Support for Command and Control", IEEE Trans. on SMC, Vol. SMC-16, pp 865-879.

Wilson G.B., 1985; Some Aspect of Data Fusion, Proc. of the IEEE Conference in Advances In C^3, United Kingdom, PP 99-104.

Discussion

DISCUSSOR : **M. S. NAYAR (UK)**

1) Outside the proposition [1], how do you assess the other propositions ?
2) How do you compute the ignorance belief ?

Author's reply :

1) In the presented situation, the algorithm select the best 8 solutions. All propositions having a combined belief higher than 10 % are retained. If there is still places, the algorithms selects the propositions having only 1 element by increasing belief. Il again there is places, the algorithms selects the 2 elements, and so on.
2) After the selection of the 8 best solutions, the ignorance receives the beliefs of all the other propositions.

THE CASE FOR A DUAL MODE DEFENSE SUPPRESSION WEAPON

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SUMMARY

This paper explores the issues involved with setting the requirements for a dual mode, defense suppression weapon. Many important issues that drive requirements for a defense suppression weapon are discussed in order to develop a framework or methodology under which requirements for new weapon systems can be developed. Traditional defense suppression thinking and Desert Storm experience merge to form the methodology for choosing defense suppression options.

The paper starts with the global requirement that friendly aircraft must fly to intended targets unthreatened by radar guided weapons. This requirement leads directly into many traditional anti-radiation weapon issues as well as many of the issues from Desert Storm. Some of the issues explored are detection, location, targeting, mid-course guidance, terminal guidance, warhead lethality, battle damage assessment and cost. In addition, requirements for dual mode systems (passive radio frequency seeker and imaging seeker) are discussed for missions conducted in the presence of non-radiating, operational, threat systems.

The goal of this paper was to provide a framework or methodology from which one could quantify the requirements for a destructive defense suppression weapon in terms of cost, resources saved and expanded tactical capability.

1. INTRODUCTION

Defense Suppression is the act of suppressing the enemy's ground based air defense capability through the use of lethal or non-lethal means so that aircraft can conduct missions with minimal risk. Lethal defense suppression implies the use of mechanisms (missiles, bombs, lasers, electo-magnetic pulse (EMP), etc.) to physically damage or destroy air defense equipment. Non-lethal defense suppression is used to deny the enemy the use of their air defense equipment through the use of electronic jamming, chaff and decoys. The major argument in favor of lethal defense suppression is that once destroyed, an element of an air defense system will not be available to threaten air missions on subsequent days. We will limit our discussion in this paper to lethal defense suppression.

2. BACKGROUND

The modern age of defense suppression or Suppression of Enemy Air Defenses (SEAD) began during the Vietnam conflict. The SHRIKE missile was developed to home on the electromagnetic emissions of the threat radar; hence the technique of Anti-Radiation Homing (ARH) was initiated. The ARH technique was improved through the years through a series of SHRIKE, Standard Arm, and currently HARM missiles. As a result, the term defense suppression or SEAD became synonymous ARH missiles.

3. PURPOSE

The purpose here is to develop a systematic methodology to define requirements for a lethal SEAD weapon system. This paper attempts to include the important issues that may drive the requirements and to show how they should influence the design. Example requirements are included to illustrated the methodology.

4. APPROACH

The first step in this approach is to define the mission requirements for a lethal SEAD weapon. The requirements must be specifically defined in terms of the period of time they may span and the geographic areas where they may be carried out. The ground based threat systems that are to be suppressed must be listed and grouped according to their lethal range.

The second step is to identify the defense suppression functions that must be performed in order to accomplish the mission requirements. Some of these functions may be already fulfilled by existing systems.

The third step is simply to identify technologies that can be used to perform the required functions.

5. MISSION REQUIREMENTS

We first start with the global requirement that friendly aircraft must be able to perform their assigned missions, unthreatened by ground based weapon systems. This means that the enemy's air defense systems on the ground must be suppressed during the time the friendly aircraft are in the area. The expected types of missions to be flown by friendly aircraft and the threats likely to be encountered are included in the

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mission requirements. Two mission types and three threat categories will be used for an example throughout this discussion.

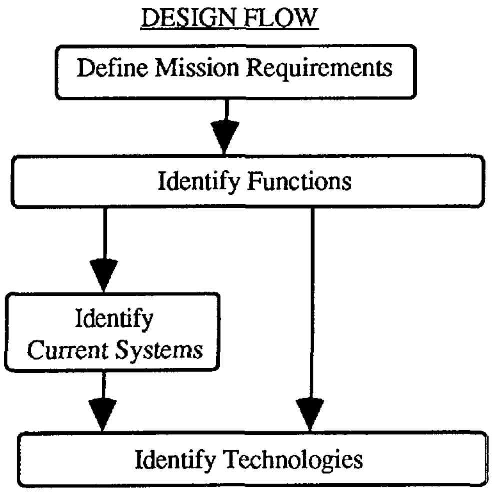

Figure 1

5.1 Mission Types

Mission type I is a quick, single strike, deep into a hostile area against a specific point target. The time over which defenses must be suppressed is very short. This mission may require preemptive as well as reactive SEAD. Battle damage assessment (BDA) after the lethal SEAD attack against the air defenses may not be important. Type I missions can use decoys to good advantage. Ground based systems that do not radiate are not a problem since they only degrade their own capability to engage our aircraft.

Mission type II is a prolonged campaign carried out over a wide area. The ground based air defenses must be suppressed for days or weeks. BDA would be very important as the SEAD efforts progressed. This mission may require preemptive as well as reactive SEAD. Type II missions can use decoys to good advantage only in the early engagements. All ground based defensive systems must be suppressed (destroyed) whether they radiate or not. This is a mission requirement to attack non radiating targets.

5.2 Threats

First, the geographic areas that may be attacked in the future need to be identified. Having the specific areas identified will help define the types and numbers of threats that must be suppressed.

Next, the types of threats that need to be suppressed can be divided into categories based on their effective range. The range at which SEAD launch platforms must stand off from a ground based air defense system will determine the type of weapons required to destroy it. The lethality of the system must also be factored in to determine how important the threat is in terms of its capability to destroy friendly aircraft.

Another factor is the mobility of the threat system. The systems mobility will greatly influence the targeting methods used to destroy it. A system's vulnerability to countermeasures can also be factored in. If a particular system can be neutralized by on-board countermeasures, it may not be necessary to devote assets to destroy it.

It is also important to consider how may systems there are in the world or in the regions of interest. This is an intelligence issue. It may not be cost effective to place stringent requirements on our defense suppression weapon because of only a few exotic threat systems.

For our example we will use three generic threat categories based on range.

	Range	Number of Systems
a.	short	many
b.	medium	moderate
c.	long	very few

Short range covers most point defense threat weapon systems. Medium threat systems are the main area defense systems we see in the world today. The long range category is for the very large and complex defensive systems.

Once the threats have been categorized, the requirements for each category can be developed. The ideal but costly approach would be to define a system that will meet the requirements for all categories. The advantage of categorizing the systems is that some of the very modern, high value systems separate into a category of their own. These systems are very costly and so, not prevalent in world.

We have now defined the example mission requirements in terms of the types of mission and the threats likely to be encountered. The next step is to identify the needed functions to meet the mission requirements.

6. IDENTIFY FUNCTIONS

Analysis of the mission requirements will allow us to summarize the SEAD requirements as a set of functions that must be performed. These functions will be such that they fulfill the mission requirements. In order to meet the mission requirements five functions must be performed. (figure 1)

The first function to be performed is the location of targets in the area of interest. Some type of sensor must be available to detect both radiating and non radiating targets. All located targets must be identified to determine the threat they pose to the aircraft. After a target is located and identified, its position must be passed to a system that is able to deliver some type of warhead to that target. This system must guide to the area of the target and destroy the target. After the site has been attacked, the results of the attack must be assessed to determine future actions. This evaluation function is called battle damage assessment (BDA) or battle damage indication (BDI).

The system requirements for a defense suppression weapon are dependent on the capabilities of the targeting assets. The locate and identify functions will be performed by existing or planned targeting assets.

These assets must be identified and characterized in order to properly develop the system specifications.

Some examples of targeting assets are satellites, JSTARS, and wild weasel type aircraft. The operational control of these assets and their availability are very important factors when considering their utility for defense suppression. In addition to these traditional targeting assets, there may be some utility in small, tactical targeting drones.

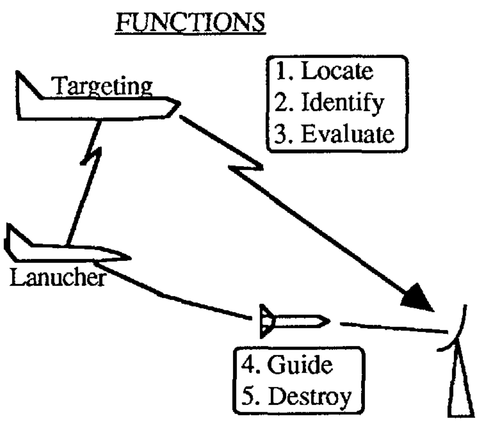

Figure 2

While the targeting issues are very important to the specification of our system, they are far beyond the scope of this discussion. We have to allow that the first three functions (locate and identify targets, evaluate results) are performed by the targeting assets or the launch platform. We are only interested then in the information that might be available to our defense suppression weapon from the launch platform.

7. GUIDE FUNCTION

The guide function consists of mid-course and terminal. Mid-course is the action getting to the target area based on initialization data and target location data. The terminal guide function consists of acquiring target, then tracking it until impact. The terminal function must include some type of target recognition in order to avoid guiding to false targets.

A terminal sensor is required to provide the final position of the target. Midcourse systems including the global positioning system (GPS) should not be used for terminal unless the weapon uses a very large warhead or some type of area warhead (possibly sub munitions). In general, a weapon will be much more effective if the there is some form of terminal guidance that can achieve miss distances on the order of a few feet.

7.1 Launch Information

In order to perform the guidance function our weapon system must receive target data and possibly initial location data from the launch platform. The target data consists of the location of the target and some type of target description that will allow the weapon to select the desired target.

The initial location information provided by the launch platform consists of attitude and position. Some platforms may not be able to provide accurate position information at launch. Usually, accurate attitude and altitude information are available.

The target location information can be provided with as little as bearing alone or bearing plus range. Target location data can also be provided in terms of latitude and longitude

Historically the target description data passed to the missile has consisted of electronic intelligence information tailored to allow target recognition using a passive radio frequency (RF) system. Since we assume that the target has been recognized by targeting assets, the target type is available to be passed to our weapon system. We may get some type of target parameters based on the target type that would allow automatic target recognition. An encoded image of the target could also be provided at launch to specify the target.

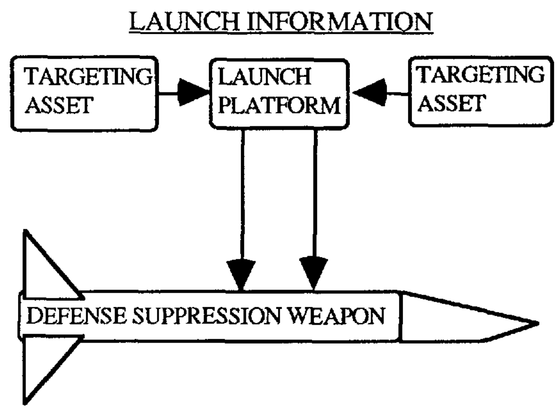

Figure 3

8. DESTROY FUNCTION

When a vehicle gets to the target it then must destroy that target, usually with an explosive warhead. At this point in our development we need to specify the lethality of our system.

8.1 Lethality and Survivability

A defense suppression weapon must survive the flight to its target in order to deliver a warhead to destroy the target. The overall effectiveness of the system must be specified so the individual factors such as survivability and lethality can be budgeted.

The overall effectiveness should be based on the cost of the system, expected number of systems and the number of systems that might be used on a mission. If the system is large and expensive then only a few might be used on a particular mission. If only a few are available then the overall effectiveness of the system must be very high. If the system is cheap and plentiful, the individual weapon effectiveness may be somewhat less than 1.0. For our example, let us specify that we want our system to have an overall effectiveness of 0.7. If we assume that the individual factors are independent the following table shows a sample effectiveness budget.

reliability	.98
probability of acquisition	.90
probability of survival	.90
probability of kill	.90
Overall Effectiveness	.71

There are BDA/BDI issues to be considered when specifying the systems lethality. The type of damage mechanisms used can aid in the BDA/BDI stage. EMP for instance, will give no clue as to the damage it produced while the damage from a 2000 pound high energy warhead can be easily seen from the air.

In addition a fusing function must be provided that activates the warhead at the proper time.

9. FUNCTIONS SUMMARY

The locate and identify functions are performed by existing or planned targeting assets. The type of information available from the targeting assets will drive the guidance function requirements for both midcourse and terminal systems. The destroy function can be specified in terms of lethality and survivability. Now that the functional requirements have been defined we can examine general technologies that can be used to meet those requirements.

10. AIRFRAME TECHNOLOGY

The airframe issues are range, survivability, payload, propulsion and cost. All of these issues must be worked together in order to meet all the requirements.

10.1 Range

The range requirement for the airframe is driven mainly by the effective range of the threat. The optimal solution then is to simply specify a range that is greater than the effective range of the longest range system. This may or may not be technologically or economically feasible. If we need some relief we can consciously omit the longest range system or systems from the mission requirements, assuming that other methods will be used to suppress these systems. If there are only a few of these systems, the omission may be acceptable.

10.2 Survivability

High speed and low observable technologies offer survivability enhancements. Speed is a parameter that will be constrained by seeker and propulsion choices. Vehicles traveling at high speed will experience radome heating. Radome heating can impair most imaging infra-red systems. Most surface to air missile systems are built to deal with high speed penetraters. It's the high speed coupled with the small size of the missile that impairs the fusing of surface to air missiles designed for larger vehicles.

Low observability has to be taken as a whole. If the vehicle is stealthy for instance but the sensor is synthetic aperture radar system, the vehicle may be easily detected by its radar emissions. If an active sensor is used some sort of emission control must be observed.

10.3 Payload

This is a system design specification. The payload requirements may drive the choice of airframe. There are many current airframes to choose from such as the Maverick, the Joint Stand Off Weapon (JSOW), the Improved Tactical Air Launched Decoy (ITALD) and various cruise vehicles.

10.4 Propulsion

If we need only 60 km of range we can use solid propellant such as the current HARM uses. If we need over 100 km of range we may need to think in terms of a cruising vehicle with a turbofan motor.

11. GUIDANCE TECHNOLOGIES

Historically passive RF systems have been used to guide during mid-course, recognize the target, then guide during terminal. Because of our requirement to attack non-radiating targets we must consider other sensor and guidance systems. We will include for consideration a generic imaging system capable of performing Automatic Target Recognition (ATR), an Inertial Measurement Unit (IMU) and a Global Positioning System (GPS). Table 1 lists the four guidance methods as well as what guidance functions they are able to perform.

GUIDANCE METHODS

	RADIATING		NON-RADIATING	
Guidance Methods	Mid Course	Terminal	Mid Course	Terminal
Passive RF	yes	yes	no	no
Imaging/ ATR	no	yes*	no	yes*
IMU	yes	no	yes	no
GPS	yes	no	yes	no

*Automatic Target Recognition (ATR) is never perfect.

Table 1

11.1 Terminal

When looking at table 1 we see that a passive RF guidance system is able to perform the midcourse and terminal guide functions when the target is radiating. Remember that terminal includes both target recognition and terminal guidance. The passive RF system can do nothing if there are no emissions from the target.

Table 1 shows that the imaging system can recognize the target during the terminal phase but can not mid-course guide to the target. Most imaging systems that can be carried on missiles have a very short acquisition range making them unsuitable for guiding to the target during mid-course. Table 1 shows that the IMU and GPS systems are able to guide the weapon to the target but are unable to provide the terminal functions of guidance and recognition.

Since we have the requirement to attack non-radiating targets (type II missions) and we must provide terminal guidance, we must choose an imaging system that is able to perform ATR. In addition, we must specify either an IMU and/or a GPS system to guide our weapon to a point were the imaging system can acquire the target.

A type I mission may require a passive RF sensor in order to perform reactive defense suppression. For example many missiles may be launched into an area to 'clear a corridor' for attack aircraft in a type I mission. The missiles would be expected to attack any threat that radiated.

The passive RF system could be eliminated from consideration when considering type II missions where we specify systems to function against non-radiating targets.

11.2 Midcourse

We have to specify the requirements for the midcourse guide functions so that they are matched with the location and target information that are passed to our weapon from the launch platform. These considerations will help us pick between an IMU and GPS.

If the target is specified in earth coordinates and the launch platform can provide accurate initialization we could choose an IMU since a typical time of flight for our system may be relatively short. A GPS system in our weapon would be required if the targets were specified in earth coordinates and the launch platform could not provide accurate initialization data.

12. WARHEAD TECHNOLOGY

Here we are finally at the warhead. A systems approach must be taken in designing and sizing the warhead. If the terminal sensor is very accurate and the missile has sufficient endgame maneuverability then the resulting circular error probable (CEP) could be very small. A small CEP will require only a small warhead and of coarse a large CEP would require a large warhead. It is possible to have a very accurate missile with no warhead, using only the kinetic energy of the vehicle as the damage mechanism.

Warheads can either be unitary or sub munitions. There are some exotic concepts such a directional warhead or EMP that might be worth considering. The EMP warhead really compounds the BDA problem because there is no external evidence that the victim system is disabled.

13. CONCLUSIONS

The mission requirements were defined in terms of the types of missions and the threats that are to be suppressed. From the mission requirements the functional requirements were derived. Finally, technologies were applied to meet the functional requirements.
Here are some of the requirements:

- A cruising system (long range)
- INS and GPS
- Passive RF
- Imaging terminal sensor with ATR

This system could be called a tri mode system if one counts the GPS. This type of system is what has historically been called a dual mode defense suppression weapon because of the passive RF and the terminal sensor for non-radiating targets.

Except the ATR functions, this system could be built from existing, off the shelf components.

DESTRUCTIVE SUPPRESSION SIMULATION FIDELITY

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SUMMARY

A study of the analytic process used to determine the effectiveness of destructive suppression has been conducted which considers two software packages (a lumped parameter package and a detailed point burst methodology) four target model data bases of varying complexity, and two warhead data bases (one simple and one highly detailed). The study parametrically matches the warheads, targets, and software tools and looks for the convergence of results. Also, the combinations which diverge most widely are noted and an effort is made to explain the range of results.

After looking at the results several pertinent conclusions can be drawn regarding actual destructive suppression effectiveness and apparent simulation fidelity. For many antiradiation missile (ARM) encounters, with their attendant small miss distances, a good analytic assessment can be made using quite simple methods and data. It is possible that using the more detailed models and programs pays off in the area where the damage mechanisms are discrete and the energies involved are relatively small. It appears that for guided weapon lethality analysis, the value added by using high fidelity tools may be only marginal.

INTRODUCTION

This paper presents the results of a study which looked at the connection between simulation fidelity and accuracy of results. The type of simulation examined was an analytic process which determines the terminal lethality of high explosive warheads used in anti-radiation missiles. The specific aspect of the simulation considered in this study was the level of detail of the target model used in the analysis.

ANALYTIC PROCESS

Before giving the results of the study, the analytic process used to calculate weapon terminal effects will be summarized. The process, illustrated in Figure 1, consists of 4 major parts. Three of these parts are input data files and the fourth is a computer program which processes the input data to calculate a measure of the damage produced and a measure of target system degradation. The level of degradation is related to a particular function of the target, like launching or controlling a missile, and is generally expressed as a probability that the function can no longer be performed. For destructive warheads, this probability is referred to as probability of kill, or Pk.

The computer program which forms the core of the analytic process is a mixture of empirically derived algorithms and algorithms based on pure mathematics and physics. For example, the equations in the program which calculate the probability that a warhead fragment will strike a certain target element are derived from fundamental

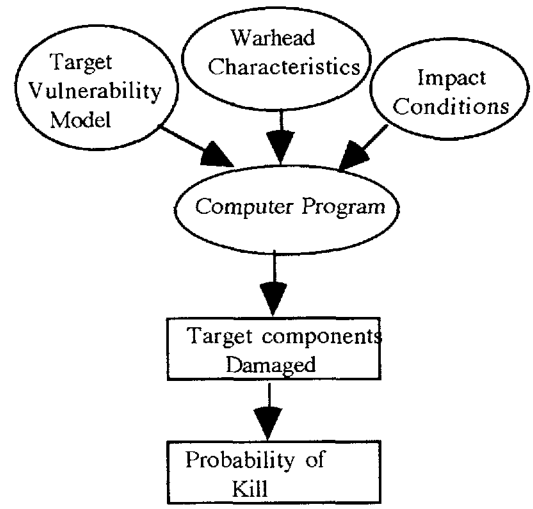

FIGURE 1. Analytic Process Used to Evaluate Destructive Suppression Capability

statistics. However, the equations which predict the residual energy of that fragment once it has perforated the element are based on laboratory tests conducted specifically to develop the relationships between fragment characteristics (shape, size, material, density, velocity), target characteristics (material type, thickness) and residual energy. With extensive laboratory testing and the correct application of mathematics and physics, a computer program can be written which can replicate many types of live fire events and predict weapon effects with a large measure of credibility.

The warhead characteristics data file is a collection of information which is a measure of the total energy produced by the warhead and the distribution of that energy in space. This data file is based on actual firings of full scale insitu warheads. It consists of information like: the number of fragments produced, their weight, shape, material type, and speed, and a direction vector for each fragment (or perhaps a small group of fragments). Warhead data files can be considered as being thoroughly validated due to their empirical basis. Typically they are not large because many fragments often have similar weights and velocities. At any rate, a warhead file poses no serious data storage or computational challenges to today's high capacity computers.

The data file containing the impact conditions is the smallest file, but it can be very critical to the analysis outcome. This file contains information like weapon impact angle (azimuth and elevation), impact velocity and hitpoint or detonation point relative to the target center. If the weapon's warhead cannot direct energy onto the target (the result of an undesirable impact angle for example,) then target damage will be modest even when miss distances are not large. The contents of the impact condition file

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are, again, based on actual missile firings and can be accepted with a high degree of credibility.

The target vulnerability data file is typically the most complex and unfortunately the least well validated. This file contains a geometric model of the target, a functional model of the target, and vital component vulnerability data. The geometric information describes the size of the target and details the materials used and their thicknesses. The functional information identifies components that are vital to the mission of the target and, using a fault tree (disablement diagram), defines how various components play together so the target can operate properly. The type of damage (kill criterion) one is interested in determines which components are vital. For example, if the target is a mobile surface-to-air missile system, and the kill criterion is loss of firepower capability, the launchers will be vital but the main drive shaft may not.

For the target components which are determined to be vital, the target file also contains vulnerability information. This information often takes the form of vulnerable areas which are a function of fragment weight, velocity, and material type. The data are quite detailed but not necessarily accurate. This is because they are based on laboratory experiments using actual fragments but surrogate equipment. The response of the surrogates to the fragment impacts is carefully observed and recorded, but when this surrogate data is placed in a target model, it suffers from a number of deficiencies. For one thing, if the surrogate is, say, an amplifier, it may not be a good frequency or power match (and therefore size match) for the real component. Also, the surrogate might be of a different technological generation. Finally, the surrogate might not be placed in the correct position in the target.

Thus, the accuracy of the process of analytically determining a weapon's destructive suppression capability reduces, in many instances, to the accuracy of the target model data file. This is an important conclusion, but before large amounts of time and funding are allocated to solve the apparent problems associated with target models, it is important to quantify the problems by understanding the influence of model fidelity on the outcome of the overall simulation process.

APPROACH

To measure the influence of target model fidelity on the total simulation process, four target data files were created for the same target. The files ranged in complexity from a simple box to a rather detailed van structure having fourteen vulnerable components. A plan view of the four target models is presented in Figure 2.

In the case of the first target, since it was so simple, a rather unsophisticated computer program was used to evaluate Pk. The program used was the Guided Weapon Method published by the Joint Technical Coordinating Group for Munitions Effectiveness (Ref 1). This program considers the target to be a rectangle and the warhead's lethality is characterized by a pseudo-area called a mean area of effectiveness (MAE). For a given weapon accuracy, the probability that the MAE intersects the target rectangle is calculated and this probability is related to the probability of kill. For Target 1 (the least detailed target), all of the Pk data were calculated using this uncomplicated procedure. The Pk data for the more detailed targets were calculated using a point burst methodology call the General Point Burst Program (Ref 2). The procedure involved in the use of this program was described in the Analytic Process Section of this report. Two warheads were used in this study to determine whether or not the size of the warhead played any significant role in establishing the proper level of target detail. One warhead was a rather light weight guided missile warhead weighing 68 kg. This warhead used preformed fragments each weighing about 0.84 gm. The total number of fragments was on the order of 25,000. These fragments were produced in the nose region of the warhead and from the sides. None of the fragments came from the rear of the warhead.

The second warhead was a general purpose device weighing 226 kg. It produces approximately 20,000 random weight fragments in all directions, but most of the fragments emanate from the sides.

The impact conditions used for this study were the same for both warheads. The elevation angle was 30 degrees, the warheads detonated at the height of the target (2.43 meters), and the warhead velocity was set at 305 meters per second. The aimpoint was the top left corner of the van. The accuracy of the missiles was measured using a statistic called the circular error probable (CEP). This is the radius of a circle centered at the aimpoint that contains 50 percent of all the weapon impacts. The CEP is related to the standard deviation, sigma, by the following equation: CEP = (1.774) sigma. For each Pk presented, 100 trajectories were flown at the aimpoint assuming a circular normal distribution. The 100 Pk values thus calculated were averaged to produce the single Pk presented for each warhead and each accuracy.

RESULTS

Figure 3 shows how Pk varies as a function of weapon accuracy and target detail for the 68 kg warhead. One of the most notable aspects of the figure is the rather close Pk agreement between all the target models at small and large CEPs. One possible explanation for this general agreement is that the warhead energy overmatches the threshold energy required to significantly damage this target. If this is the case, then the 226 kg warhead results might be in even closer agreement. This will be considered later in the paper.

The Figure 3 data are for an attack azimuth of 0 degrees. Figure 4 presents similar data for an attack from an average azimuth (Pk data for azimuths of 0, 90, 180, and 270 degrees were averaged), and it can be seen that the agreement between the models, except for the least detailed version is even closer than shown in Figure 3. This is not surprising since averaging in azimuth does have the effect of averaging certain aspects of target detail (for example, van wall material type and component locations). The data of Figure 4 do serve to emphasize that certain aspects of target detail certainly become less important when the impact azimuth is random.

The attack azimuth chosen can have a good deal of influence on the outcome of a Pk analysis, especially if the target is asymmetric and its external construction varies from side to side. This is shown in Figure 5 where Pk is plotted as a function of attack azimuth for the four targets. For the simple target there is of course no azimuth dependence and

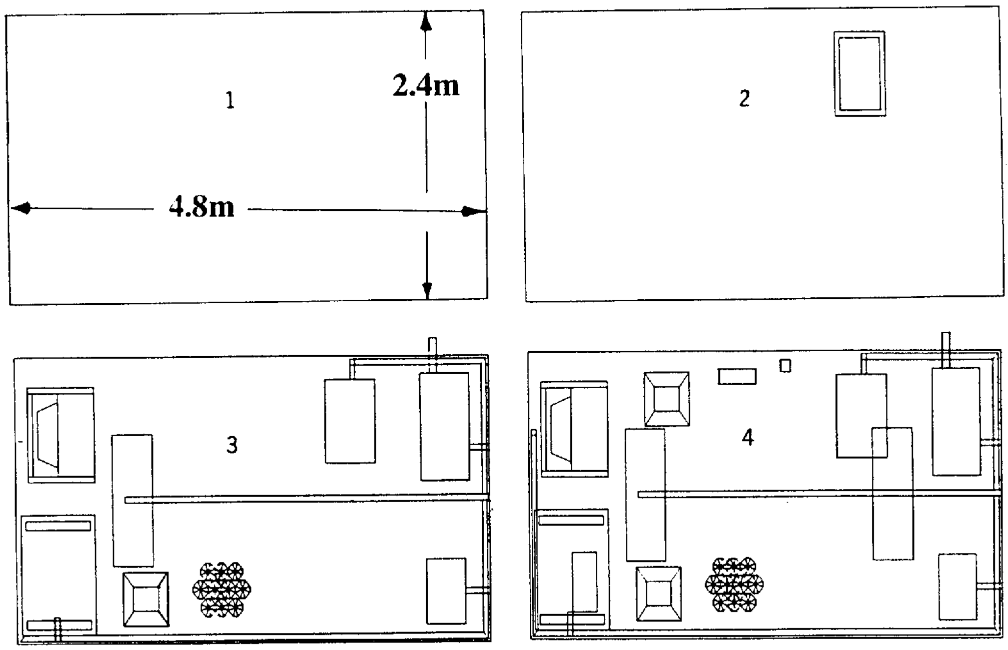

FIGURE 2. Plan Views of the Four Target Models

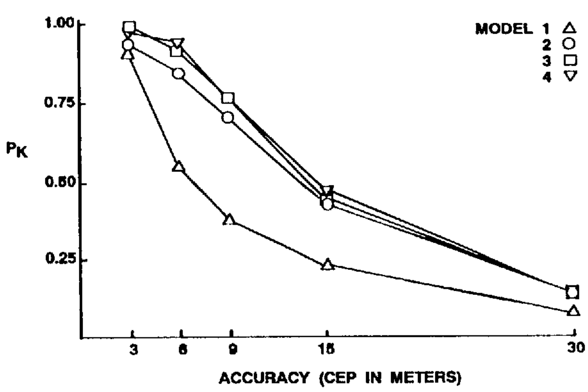

FIGURE 3. Pk Results for the 68 kg Warhead, 0 Degree Attack Azimuth

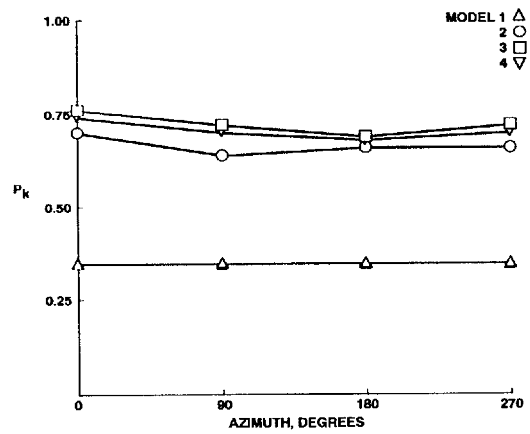

FIGURE 5. Pk Results as a Function of Attack Azimuth for the 68 kg Warhead

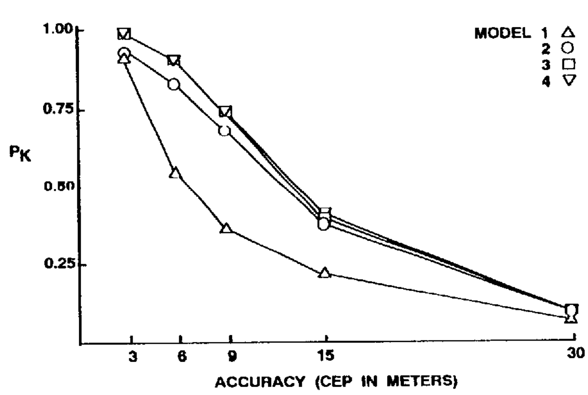

FIGURE 4. Pk Results for the 68 kg Warhead, Averaged Attack Azimuth

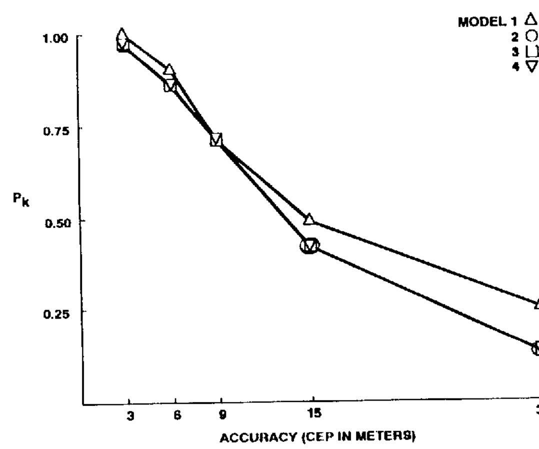

FIGURE 6. Pk Results for the 226 kg Warhead, 0 Degree Attack Azimuth

for the targets with 7 and 14 vital components, the dependence is rather slight. However, for the target with just one component it does appear that there is a marked dependence of Pk on attack azimuth. Even though for a given azimuth the difference in the results obtained with the three detailed models is modest, the overall dependence on attack azimuth indicates that for attacks from specific directions model detail assumes increasing importance.

When the 226 kg warhead is considered, as shown in Figure 6, the intuitive concept of a target threshold energy suggested by Figure 3 seems to be given credence. That is, the Pk curves for the three detailed models are so close together that differences can not be distinguished. Also, for small miss distances the simple model gives results which are almost equal to the results produced by the detailed versions. It thus appears that as the warhead size increases, less attention to target detail is warranted especially when the weapons have guided missile accuracies (CEP = 9 meters).

Considering attack azimuth variations using the 226 kg warhead yields the results plotted in Figure 7. The Pk differences for the single component target are on the order of 10 percent and the differences for the other targets are even smaller. These differences are large enough to not be ignored, but they are only important when attacks are known to occur from a specific azimuth. For surface-to-air missile radar targets, the target or its antenna is often rotating and averaged azimuth Pk data are used to characterize the attack. This alone suggests that it might be better to use an "azimuth averaged" (simplified) target for destructive suppression simulations rather than a complex target with averaged Pk results.

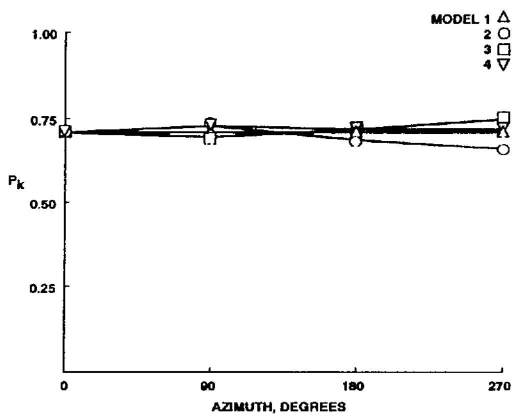

FIGURE 7. Pk Results as a Function of Attack Azimuth for the 226 kg Warhead

CONCLUSIONS

All of the data generated for this study indicate that for highly accurate (CEP = 3 meters) missile attacks, target model detail can be limited and still produce an accurate assessment of weapon effects. A similar conclusion can be reached when accuracy is quite poor, but perhaps this conclusion is moot because at large miss distances the Pk drops to near zero regardless of the target size, type or detail.

The use of very simple target models should be limited to those analyses which consider very accurate missiles. This work clearly shows that for single missile attacks with 9 meter CEPs, the simple target model yields results which are as much as 65 percent less than the best models (see Fig. 3).

For unguided weapon attacks (CEP values larger than 30 meters) it is possible that the simple model would again be useful. This conclusion might be further emphasized if multiple weapons were released, a situation not examined in the present study.

Attack azimuth is an important consideration in destructive suppression simulation. If the attack azimuth is known, it is necessary to have enough target detail to model at least the salient target azimuthal variations. If the simulation is only looking at attacks averaged over the attack direction, then high levels of target detail are not necessary.

For this particular study the Pk data converged at the third level of target detail. This was the target with more than one vulnerable component and the components were located throughout the target van. Once this was done, it seemed that the issues of absolute Pk value and its dependence on azimuth were brought rather clearly into focus.

FURTHER STUDY

Although this analysis attempted to fully address the question "How much target model detail is enough?", a definitive answer was not forthcoming. Perhaps one of the first variations of this study which should be investigated would be a comparison of single impact Pk data instead of looking at the average of 100 impacts. There might be impact points about different targets (different levels of detail) where Pk variations are quite large depending on target model fidelity.

Also, different burst heights might show effects that are more dependent on model detail than the single burst height of 2.4 meters used in this study. Related to this issue would also be the examination of different fragment spatial distributions for the same size warhead. How much target detail is required to allow a fuze designer to determine an optimum height of burst or a warhead designer to calculate an optimum fragment pattern?

One variation already suggested would be to look at multiple weapon releases. Intuitively such attacks could probably be well simulated with simple targets. However, for those creating target data files, it would be useful to have a rule-of-thumb which related level of detail to the number as well as the size of the weapons which would be launched at the target.

A final area for further study would be small warheads. When the warhead is very small relative to the target size, target detail will probably assume critical importance. Such warheads are typically not associated with airborne defense suppression, but smart submunition warhead analysis associated with interdiction strikes, might require higher fidelity target models.

REFERENCES

1. Joint Technical Coordinating Group for Munitions Effectiveness, "Derivation of JMEM/AS Open-End Methods", Aberdeen Proving Ground, Md, Rpt No. 61JTCG/ME-3-7 of 29 March 1990.

2. Naval Weapons Center, "General Point Burst Program," China Lake, Ca, NWCTM 4565-5-72 of October 1974.

AN ADAPTIVE CHANNELISED FRONT END FOR FUTURE EW

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SUMMARY

The performance of Electronic Support Measure (ESM) receiver front end technologies are compared in the context future signal scenarios. Investigation has indicated that the requirements can be achieved cost effectively by the intelligent use of front end resources. An approximate statistical comparison is given to quantify performance in high pulse densities. This shows that high Probability of Intercept can be achieved with a small degree of multiple signal capability. A self adaptive channelised receiver concept is presented. This is a hybrid of the three conventional receiver types and comprises two complementary channels which are automatically adapted to each pulse. This receiver has been developed and characterised. Practical results are presented and conclusions drawn regarding the use of adaptive receivers in Electronic Warfare.

1. INTRODUCTION

The changing requirement for future EW systems presents a major challenge in ESM design. ESM receivers must provide a high Probability of Intercept (POI) to a diverse and dense signal environment. Furthermore, the ESM receiver must have the flexibility to respond to new scenarios and new radar technologies.

Demands on the receiver are for increasing sensitivity, dynamic range and higher accuracy measurement particularly of bearing. Cost and performance are critically dependent on the ESM front end. Three technologies are prevalent in ESM - wide open, superhet and channelised. Each of these have advantages in the appropriate scenario and have limitations against particular radar signals (Ref 1). Investigations have been conducted at Filtronic into the use of a hybrid receiver front end which could benefit from each of the three traditional technologies (Ref 2).

Firstly, radar signals have been classified into four types - a) narrowband pulsed, b) wideband pulsed, c) high duty cycle and d) LPI. Optimal detection of these types requires an appropriately matched receiver. If the receiver is not matched, the POI is degraded or erroneous measurements result.

Narrowband pulsed signals are representative of radars with low duty cycles and narrowband modulation (less than 40MHz). Wideband pulsed signals are representative of radars employing wideband agility, frequency chirp or phase modulation (up to 500MHz). High duty cycle signals are representative of pulse Doppler or jamming signals. LPI represent high duty cycle signals employing modulation to enable transmission at very low power levels.

The receiver technologies have been compared on the basis of complexity, POI, corruption of measurements and suitability for measurement of each of the four signal types. These are summarised in general terms in table 1 and discussed below.

The wide open ESM receiver is based on an Instantaneous Frequency Measurement unit (IFM). This offers low cost, wideband coverage over a large dynamic range. The POI, whilst normally high, is significantly reduced by the presence of high pulse densities or high duty cycle signals. Due to the wide bandwidth of coverage the sensitivity is also low and detection of LPI signals is unlikely.

The superhet comprises a tunable downconverter with filtering. The RF bandwidth means that the superhet performance is not significantly degraded in high pulse densities. However, the superhet must be tuned across the ESM band. This gives low POI, especially to frequency agile signals. Sensitivity can be high when the video bandwidth is reduced.

A Channeliser comprises multiple narrow bandwidth measurement channels. This offers simultaneous signal measurement with high POI. However multiple measurement channels are required for full bearing and frequency coverage giving an expensive realisation. Furthermore, the spurious free, multiple signal dynamic range can be very limited in the presence of wideband signals, or due to non linear effects. This is a consequence of the use of amplitude comparison between channels to determine signal presence and frequency. Sensitivity can be increased however this increases these problems and associated costs.

It can be seen from table 1 that each of the three technologies are not optimal or appropriate for all radar signals. A hybrid receiver would be capable of providing the optimum solution however a cost effective realisation is necessary.

2. SIMULTANEOUS SIGNALS

The proportion of corrupted measurements generated by a receiver in high pulse densities can be estimated. Simplifying assumptions have been made to indicate the relative performance of the receiver types. It has been assumed that the sample consists of a large number of random uncorrelated pulses. Let it be the case that high duty cycle and LPI signals can be excluded and be dealt with separately. Let us also assume that receiver dead time is insignificant.

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Technology	Complexity	POI	Corruption	Signals	Sensitivity	Dynamic Range
WIDE OPEN	LOW	HIGH	HIGH	a, b	LOW	HIGH
SUPERHET	LOW	LOW	LOW	c	HIGH	MED
CHANNELISED	HIGH	HIGH	LOW	a, c, d	HIGH	MED
ADAPTIVE	MEDIUM	HIGH	LOW	a, b, c, d	HIGH	HIGH

Table 1 Comparison of Receiver Front End Technologies

The Poisson distribution gives the probability of k events occurring in unit time as (Ref 4)

[1]

$$p(K) = \frac{R^K}{K!} \exp(-R)$$

where K = 0,1 ....n
R = average number of events per unit time

Thus for a measurement time τ_m the probability of K events during the measurement time is

[2]

$$P_m(K) = \frac{(R\tau_m)^K}{K!} \exp(-R\tau_m)$$

If the events have an average duration of τ_p then the probability of K events during the measurement time can be given by

[3]

$$P_m(K) = \frac{[R(\tau_p+\tau_m)]^K}{K!} \exp[-R(\tau_p+\tau_m)]$$

For example let

$R = 0.5 \times 10^6$ pulses per second average
$\tau_p = 1 \times 10^{-6}$ seconds average

For valid frequency or bearing measurement assume

$\tau_m = 100$ns

For valid pulse width or modulation on pulse measurement on average $\tau_p = \tau_m$

This example is calculated in table 2.

The conclusions drawn from this analysis are that the probability of any overlap in high pulse densities is high. Thus if the receiver can only measure one signal correctly eg: is wide open, the probability of corrupted measurement is high. However, if the receiver has the ability to correctly measure a small number of overlapping signals the probability of corruption is low. A channelised receiver would have typically only 2 active channels for the majority of the scenario. This redundancy is not cost effective.

This analysis has led Filtronic to develop a hybrid design which can adaptively measure overlapping signals and can exclude high duty cycle signals. This is also a suitable receiver for all four radar signal types.

The hybrid receiver described below employs all three of the conventional receiver technologies in a configuration which utilises features from each of the technologies whilst overcoming the major limitations.

The three receivers are controlled efficiently and rapidly to give optimal performance. This front end is denoted the Self Adaptive Channeliser (SAC), (Ref 3).

3. THE SELF ADAPTIVE CHANNELISER CONCEPT

The SAC is aimed at providing high integrity measurement of overlapping signals close in frequency over a high dynamic range. The design therefore channelises the band into a minimum number of channels. These channels are rapidly steered onto the signals on a pulse by pulse basis, thus achieving efficient usage. The basic configuration consists of two channels. The main channel measures the signal and adaptively notches around the signal. The second channel adapts to a narrowband pass around the signal. This allows measurement of two overlapping signals. The main channel is free to measure a new signal whilst the original signal is monitored in the narrow channel.

The main channel is a wide open receiver preceded by an adaptive filter (switched multiplexer). The secondary channel is a very high speed superhet preceded by a delay line. Thus an ESM system can be configured, as shown in figure 1, which gives wide coverage with high integrity DF.

The SAC performs measurement of frequency, pulse width (PW), TOA, Amplitude and Modulation on Pulse (MOP). It also cues the superhets in direction (DF) channels via a common local oscillator to perform DF measurement. Short delay lines in each channel guarantee leading edge measurement. Thus the DF channels consist of low cost narrowband components.

The SAC operates at a common IF frequency. In the advanced SAC the IF is 3 - 5GHz. To achieve broadband frequency coverage either the single SAC is intelligently controlled over the band, or the SAC can be used in conjunction with a 2 - 18GHz based wide open system.

Number of overlapping pulses during measurement	Cumulative Probability of overlap Frequency/Bearing Measurement	Cumulative Probability of overlap PW/MOP measurement
0	0.606	0.37
≤ 1	0.909	0.74
≤ 2	0.985	0.925
n	→ 1.0	→ 1.0

Table 2 Probability of Overlaps during measurement

The processing associated with the SAC is a key element allowing the entire ESM system the flexibility to adapt to the environment, and to give optimal system performance in new scenarios.

The SAC automatically converts pulses within the 2GHz IF into the narrowband channel. This enables MOP analysis and priming of jammer systems eg: Digital RF Memory.

4. THE SAC DESIGN

The SAC front end has been designed to operate at 3 - 5GHz. This is sub-octave avoiding harmonic spurious and allowing a simple superhet design. This gives a high dynamic range whilst minimising complexity. Printed filter technology is applied to give a compact implementation. The SAC design is detailed in Ref 3 and briefly summarised below.

The SAC consists of a wideband (WB) unit and a narrowband (NB) unit as shown in figure 2. The wideband unit consists of a 20 channel switched multiplexer (SWMUX), a RF log amplifier, a 20 channel channelised frequency activity detector (FAD) and a single tier wide open frequency discriminator.

The switched multiplexer which allows a notch to be switched in anywhere across the 3 - 5GHz band. This therefore enables a signal to be removed from the wideband system. The channeliser gives fast frequency measurement in low SNR and enables LPI detection.

The narrowband unit consists of a delay line, a high speed synthesiser and a narrowband pass and notch filter. All three channels have full parameter measurement.

The SAC front end is controlled by dedicated high speed circuitry. The SAC is programmable via a two way link to a processor. This allows a high degree of software control enabling several operational modes - adaptive pulsed, CW parking, blanking, chirp tracking and superhet.

For further flexibility and greater multiple signal handling additional narrowband units may be added. These are cued by the single wideband unit.

5. PERFORMANCE

The individual subsystems described above have been developed and a set on time of 140ns demonstrated. Preliminary practical evaluation of the front end has been performed, and is summarised in table 4. Tests have shown the capability of correct overlapping signal measurement over a wide dynamic range with a 2GHz instantaneous bandwidth. An effective channelisation of 40MHz has been achieved. Thus the signal separation and POI of a 50 channel channeliser are attained by a two channel design. The two signal dynamic range has been demonstrated to be 55dB typically.

Instantaneous coverage	:	3 to 5GHz
Set on Time	:	140ns
Dynamic Range	:	55dB two tone, typical 60dB single tone, minimum
Signal Separation	:	40MHz
Sensitivity (99% Detection)	:	-70dBm, typical
Noise Figure	:	11dB
Pulse Width Range	:	50ns to CW
Throughput	:	>1M pulses/second
LPI Sensitivity	:	-84dBm typical

Table 4 SAC performance

6. CONCLUSION

An adaptive front end offers several performance advantages over a fixed front end. The front end requires extremely fast subsystems to be integrated together in a configuration which enhances the performance of each of the component parts. A configuration has been presented with specifically developed subsystems. This has been shown to have a high multiple signal dynamic range leading to high POI.

REPORTS

1. Thornton M J, "Performance Limitations of Conventional ESM Systems", Filtronic Components Ltd report, NUW73A/2755, November 1987.

2. Mardia H K, "Adaptive ESM Architectures for High POI", Filtronic Components Ltd report, NUW73A/2755, February 1988.

3. Mardia H K, "Advanced Self Adaptive Channeliser Design" Filtronic Components Ltd, November 1991.

4. Munday A J, Farar R A, "An Engineering Data Book", Macmillan Press, 1979, ISBNO333258290

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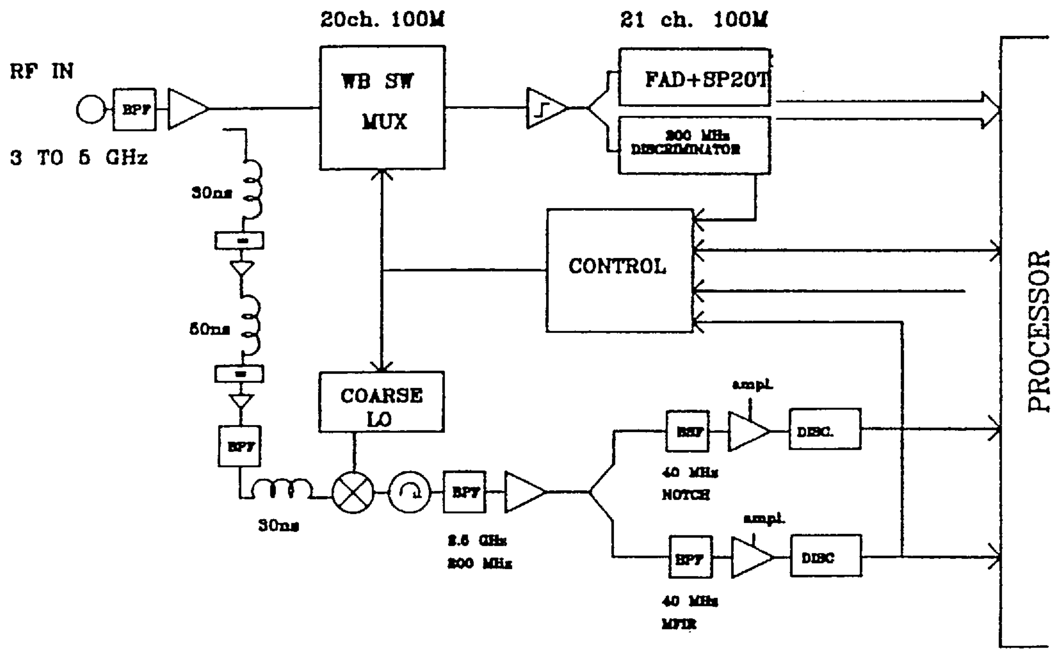
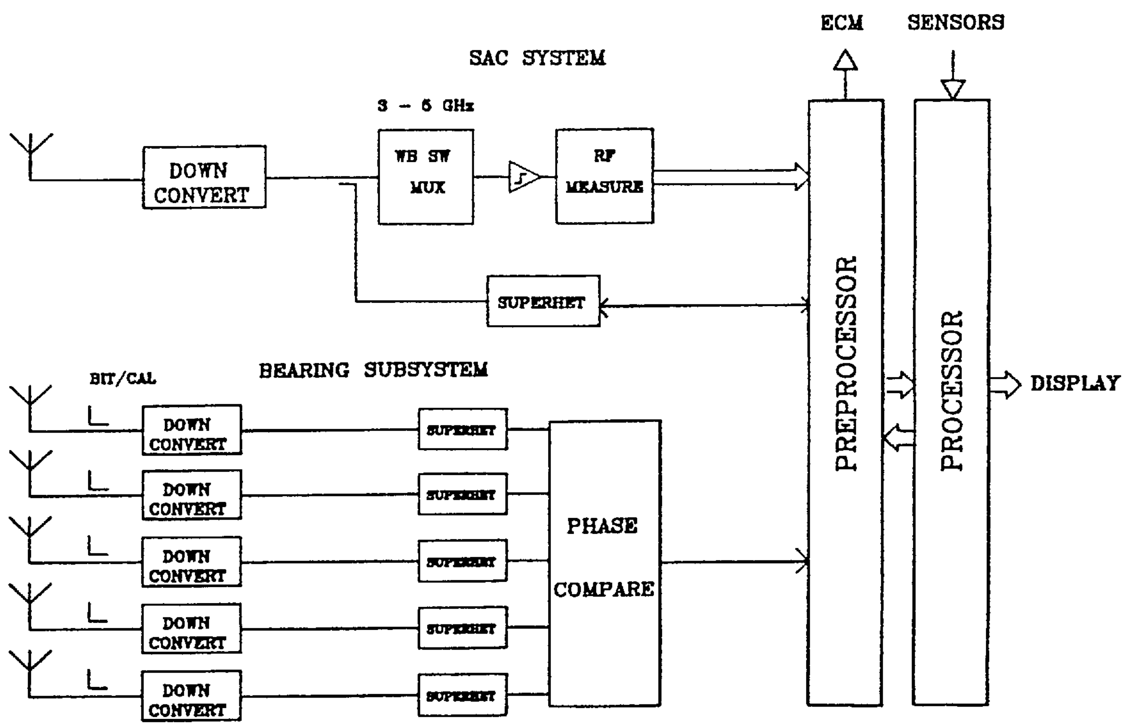


2. SAC ARCHITECTURE



1. ADAPTIVE ESM SYSTEM

Rulebased De-Interleaving System

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Summary

The complexity and diversity of future threat scenarios will be the major design drivers for EW-systems. One important issue will be the quick response to new or changed threats and tactics. Emerging technologies such as expert systems could provide effective solutions to this problem due to their inherent flexibility, e.g. their capability of simply adding or deleting rules according to new knowledge. To explore this potential, a prototype of a de-interleaving expert system was developed and tested.

The concept of the system is described. The system was developed using PROLOG on a PC platform. Tests of the system performance using real and simulated pulse train data show its capabilities and limitations.

The prototype demonstrates that with only a few simple general rules, good performance can be achieved, thus demonstrating an approach highly insensitive against scenario changes.

1. Introduction

The increasingly complex and agile waveforms of modern radar systems, combined with the lack of knowledge of all of the possible modes of threat radars (Wartime reserved modes - WARM), pose a challenge to all EW-systems that need a priori information of the expected waveforms to perform their task. Unknown or unexpected parameters or behaviour of emitters result in adding new parameters to emitter libraries (ELIB) or even adaption of algorithms to the new scenario.

New technologies such as expert systems provide a promising tool for reducing the time necessary to account for such adaptions. The objective of this paper is to apply concepts of expert systems to an EW problem and to exploit the potential advantages inherent in that approach using the de-interleaving problem as an example.

2. Characteristics of Expert Systems

Expert systems can be successfully applied to

- specific areas, where
- expert knowledge

is available but no consistent and complete theory exists.

The building blocks of an expert system are shown in figure 1.

It can be seen that an expert system is characterized by a strict separation of

- the facts and rules that are relevant to the problem to be solved (the data base) and
- the knowledge of how to manipulate and combine the facts and rules in order to solve the problem (the inference machine).

The main advantage of this separation is that adding, deleting or changing any rules in the data base is rather straightforward and does not require major time consuming software changes.

The rules can easily include higher level knowledge that is derived from e.g. military tacties or radar system design.

The latter capability will make such a system robust against scenario changes, while the former capability will allow fast adaption if necessary.

The use of expert systems can improve the performance of EW-systems in the following areas:

- pulse train de-interleaving,
- emitter and/or platform identification and
- preflight message generation.

The characteristics of these tasks are:

- availability of experts,
- no common sense problem,
- complex but solvable problem.

These characteristics make the tasks suitable for a rulebased solution. Because of its limited com-

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plexity, the de-interleaving problem was chosen to assess the above mentioned advantages.

The rulebased system was developed on a personal computer using the 5th generation language PROLOG (Programming in Logic).

3. De-Interleaving

The problem of de-interleaving pulse trains is to assign to each received pulse an unique emitter, thus

- separating pulses from different emitters and
- identifying the (unknown) pulse repetition intervals (PRI) of the emitter.

In general, pulses can be identified by thus

- direction of arrival,
- frequency,
- pulselength,
- amplitude
- intra pulse modulation.

However, depending on the overall design, the resolution capability of actual ESM receivers will usually be limited in one or more of the above measurements, resulting in ambiguities with respect to the pulse/emitter correlation.

To test the rulebased de-interleaving system it was assumed that no further discrimination of the input pulses except for their different times of arrived (TOA) was possible.

Therefore, the only input to the system is

- the number of pulses and
- the TOA of each pulse.

On this basis the system has to decide on the number of active emitters and their respective PRI patterns, taking into account false alarms and missed detections.

It should be noted that, in principle, there is insufficient information in the TOA's alone to be certain about the assignment of pulses to emitters. The problem gets worse due to the increasing flexibility of agile waveforms of modern radars.

There are, of course, algorithms available that perform the de-interleaving tasks. They can be based on different strategies,

- e.g. to test the input data against succesively more complicated PRI patterns (starting with constant PRI), remove all pulses that match and repeat the process

and on different techniques

- e.g. histogram analysis of pulse intervals to identify different type of PRI patterns.

The performance of these algorithms will depend on their parameters (e.g. allowed number of missing pulses, gate width etc.) and the scenario (number and type of emitters).

The question then arises [1]: "How can the analyst decide which is the best? This calls for judgement, based on experience ..."

The rulebased de-interleaving system described below tries to perform the above mentioned jugdement.

4. Concept

The basic strategy of the rulebased de-interleaving system is to "generate and test".

It first step is to generate a complete set of possible solutions (active emitters) for the given input (TOA sequence).

This tree of solutions is than analyzed to find out the most probable solution, i.e. the number and type of active emitters that produced the observed pulse train(s).

Two main processing steps are involved:

- pre processing algorithms to transform the TOA sequence into "Potential PRIs" used as actual input to the rulebased part of the system and
- rules that generate and limit the solution tree and select the final solution.

The principle of the preprocessing algorithms is shown in figure 2. For each combination of adjacent pulses a tentative PRI is set up. Using time slots corresponding to that PRI, each measured TOA is tested to determine wether it belongs to that tentative PRI or not. If a sufficient number of pulses is found, the tentative PRI is changed to a potential PRI with its corresponding quality factor (i.e. number of pulses available for PRI divided by number of possible pulses). It should be noted that during this process each pulse can be assigned to several potential PRIs. Figure 3 shows a result of the preprocessing algorithms.

The next step is to establish the tree of potential solutions. It turned out to be of great importance to have rules that limit the size of the tree in order to avoid a combinatory explosion.

The branches of the solution tree are generated be taking a potential PRI as a seed. The pulses assigned to that potential PRI are then removed from all other potential PRIs, with a corresponding reduction of the quality factor. These reduced potential PRIs constitutes the next level of the solution tree. This process is repeated until no more potential PRIs are left. Figure 4 can be used to explain the process for which the data of figure 3 is used. Taking potential PRI "A" as a seed, 25 out of 26 measured pulses are assigned to that branch and no further levels are possible.

Taking potential PRI "D" as a seed, only 12 out of 26 measured pulses were assigned to that branch at that level. The pulses assigned to potential PRI "D" are removed from all other potential PRIs. This results in a changed number of pulses for PRI "a_3" and "b_1". The potential PRIs "E" and "F" have no common pulse with "A" or with each other, and are thus left unchanged.

This principle can easily be implemented using PROLOG. As figure 4 illustrates, the tree of solution can become rather large. Rules are therefore needed to reduce its size already during its generation.

One obvious rule is not to continue with the processing of branches where the quality factors are already too low.

A less obvious but very effective rule is to not process branches that include a potential PRI that is present in another branch with a significantly better quality factor.

The reasoning behind this rule is that if a certain PRI corresponds to an active emitter, and is therefore part of the potential solution, then its quality factor should be as high as possible. In other words, if the PRI "A" is a potential solution, then it does not make sense to evaluate solutions that include the same PRI with a significantly reduced number of pulse, e.g. "a_1" or "a_3".

This rule leads to a substantial reduction in the number of branches that have to be analyzed. In the example given in figures 3 and 4, the number of branches, i.e. possible solutions, is reduced from 131 to only 18.

The analysis of the remaining branches is done using only a few simple and straigthforward rules. The rules have to reflect a model of the scenario that generated the observed pulse train.

The best model of the scenario is one, that explains the observed data with the least complexity.

At the extreme, an observed pulse train could be generated by either

- one emitter with a very complex PRI pattern or by
- as many emitters as received pulses, i.e. each pulse came from an independent emitter.

Both models have to be rejected due to the complexity of the assumed scenario.

From this it is obvious that the rules implemented into the system should result in an estimated scenario with the following characteristics [1]:

- as few different emitters as possible,
- as many pulses assigned to emitters as possible,
- assuming as few missed pulses as possible,
- assuming the least PRI complexity of each emitter.

These statements can be rather easily transformed into rules. These rules have to be augmented by additional rules that deal with typical radar PRI patterns (e.g. stagger, dwell switch).

Each branch of the solution tree is assessed according to the rules which are based on the above mentioned characteristics. The branch that has the best fit to the overall set of rules is chosen as the solution.

5. Test Results

The rulebased de-interleaving system was tested using measured and simulated pulse train data.

The characteristics of the test data were:

- maximum number of pulses: 200 (hardware limitation)
- different PRI pattern (constant, staggered, dwell switch)
- jitter (20 % maximum)
- missing pulses (50 % maximum)
- several interleaved emitters (10 maximum)

The quality of the results were measured by the number of pulses correctly assigned to their corresponding pulse trains, in relation to the total number of pulses. The following results are averaged for cases where random events (jitter, missing pulses) with the same characteristics occured.

Figure 5 shows that the system needs in the order of at least ten pulses to assign more then 70 % of all pulses to the correct constant PRI emitter.

For this case the system performance gets better with an increasing number of pulses.

Figure 6 illustrates that the performance for a high percentage of missing pulses is remarkedly well. The influence of the PRI pattern (constant; triple stagger) is not very significant.

Figure 7 demonstrates that even more complex PRI patterns are correctly identified by the system.

Finally, figure 8 shows the capability of the system to de-interleave the pulse trains of several emitters, where the overall number of pulse was left constant. All of the emitters are identified and all of the pulses are correctly assigned for up to five emitters. For eight emitters, all of the emitters are correctly identified. However about 20 % of the pulse are not correctly assigned. Finally for ten emitters, the reduced number of pulses per emittter (5) results in only 50 % of all the pulses being correctly assigned.

In summary, the results show that a rulebased de-interleaving system is feasible and performs well under the conditions tested.

6. Conclusion

The experience gained by developing the rulebased de-interleaving system leads to the following conclusions:

- The application of rules to problems in the area of EW is possible. For the de-interleaving system, a limited set of simple, straightforward, and very general rules can replace more complex algorithms.

- The rules applied are inherently independent of the scenario, making the system robust against scenario changes. No a priori ELIB data is needed.

- Adaptions or refinements of the system can easily be done. Deleting rules, modifying existing rules, and/or adding new rules does not require major software changes. The sequence of rules is not critical.

Finally it can be concluded, that the application of expert systems to EW is a very promising way to increase the capabilities of EW-systems and to cope with the more demanding and changing sceanrios of the future.

Other applications of expert systems are:

- emitter and platform classification, where general rules of radar design ("reverse engineering") and military rules can be used to help identify the type and task of an emitter

- preflight message generation, where the complex problem of assigning a limited number of resources (e.g. receiver channels, ECM techniques generators, output amplifiers) against a wide variety of threat combinations in an optimum way has to be solved.

Reference

[1] Richard G. Wiley
Electronic Intelligence: the Analysis of Radar Signals
Artech House, Inc.
Dedham, MA
1985

List of Abbreviations

ELIB	Emitter Library
ESM	Electronic Support Measurements
EW	Electronic Warfare
PRI	Pulse Repitition Interval
PROLOG	Programming in Logic
TOA	Time of Arrival
WARM	War Time Reserved Mode

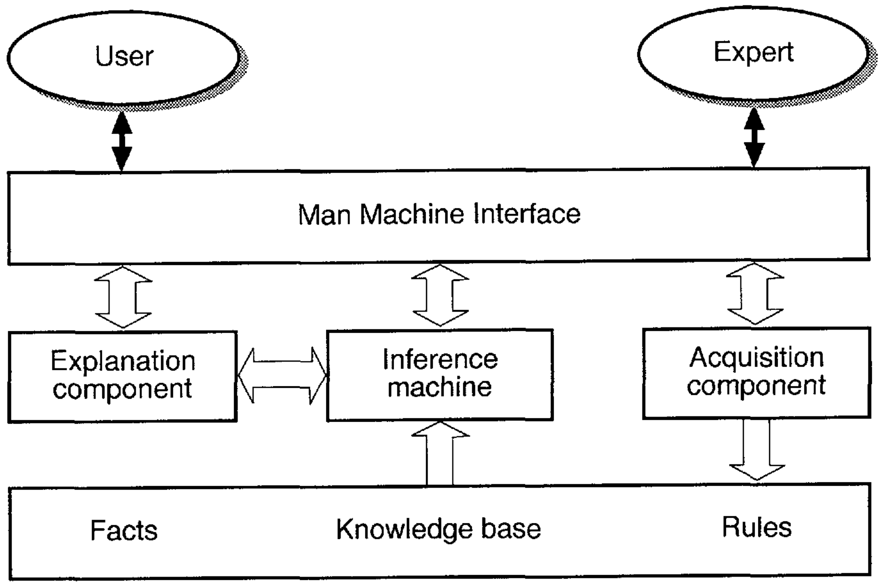


Figure 1: Generic Blockdiagram of Expertsystem

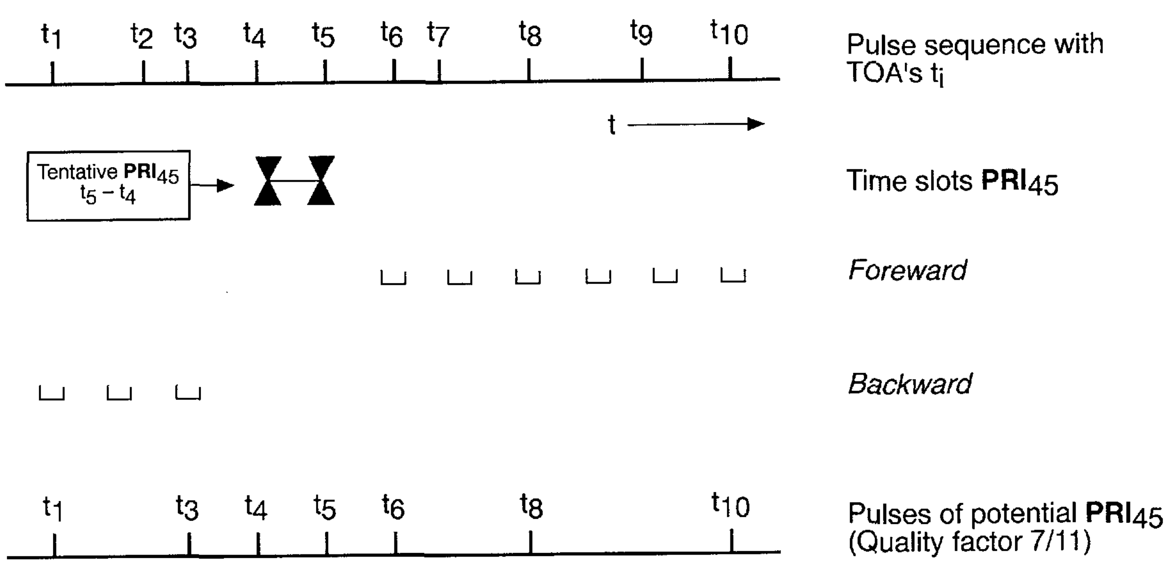
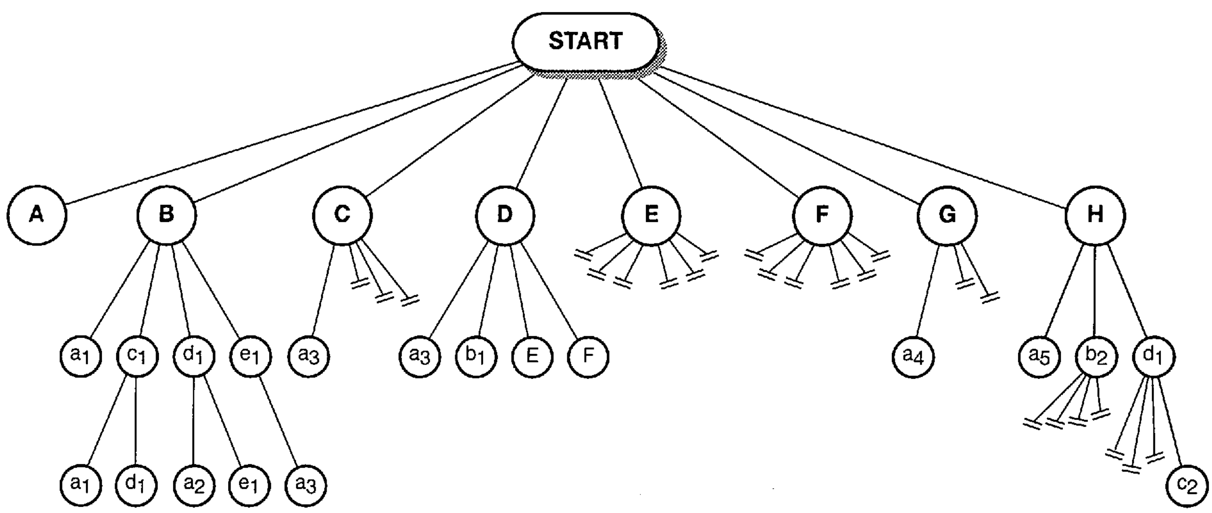


Figure 2: Preprocessing Algorithm

Duration 37 ms; 26 Pulses (TOA's)

Potential PRI	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*
PRT$_m$ (μs)	850.1	2550.36	1700.63	1700.68	3401.2	5100.7	3400.4	5100.7
Q-Factor	$\frac{25}{43}$	$\frac{15}{15}$	$\frac{14}{23}$	$\frac{12}{20}$	$\frac{9}{12}$	$\frac{8}{8}$	$\frac{7}{10}$	$\frac{7}{7}$

Figure 3: Results of Preprocessing Algorithm



a_i ... h_i corresponds to the potential PRI's A-H without those pulses that are assigned to higher level PRI's

Figure 4: Solution Tree

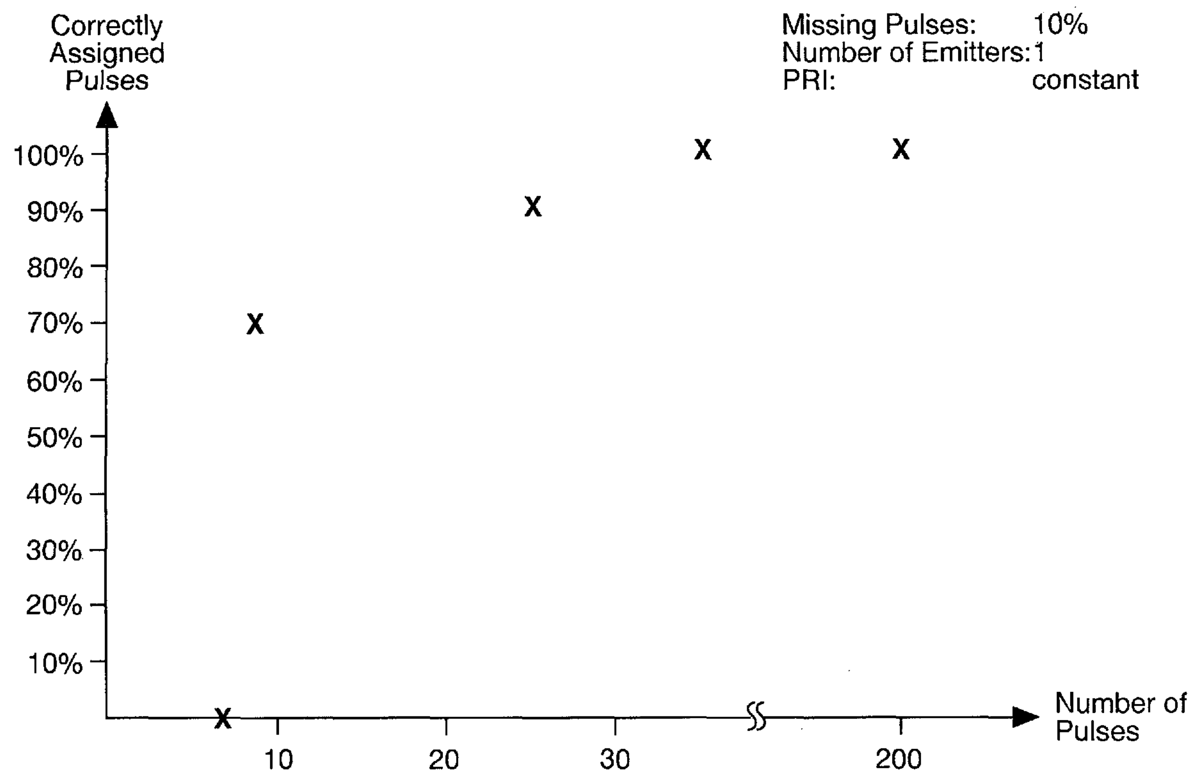


Figure 5: Performance vs. Number of Pulses

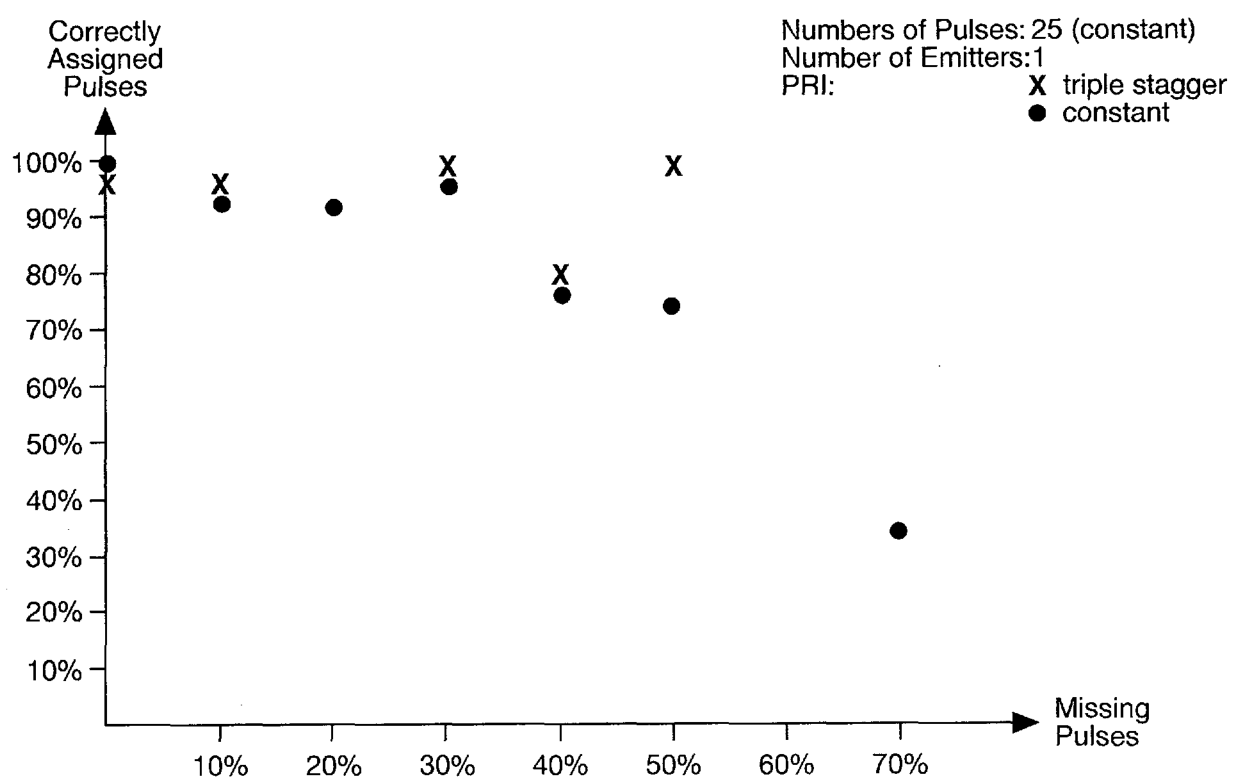


Figure 6: Performance vs. Missing Pulses

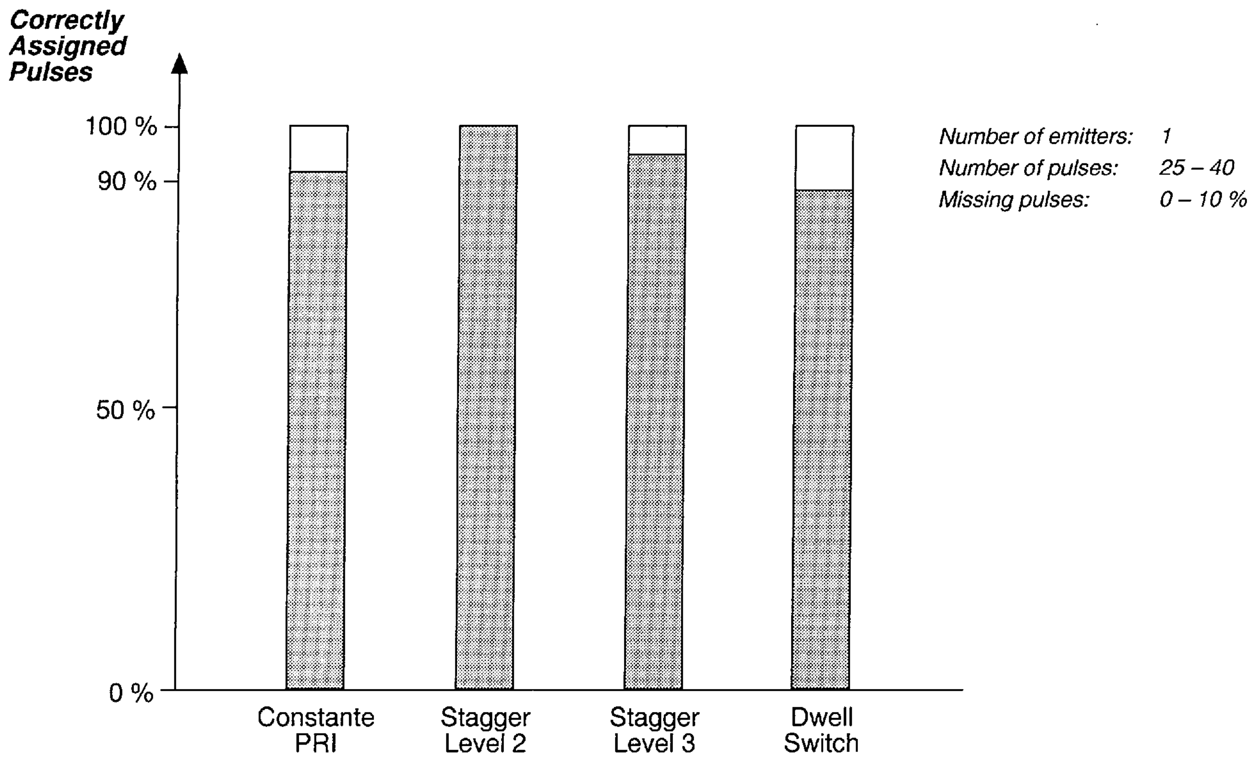


Figure 7: Performance vs. PRI-Pattern

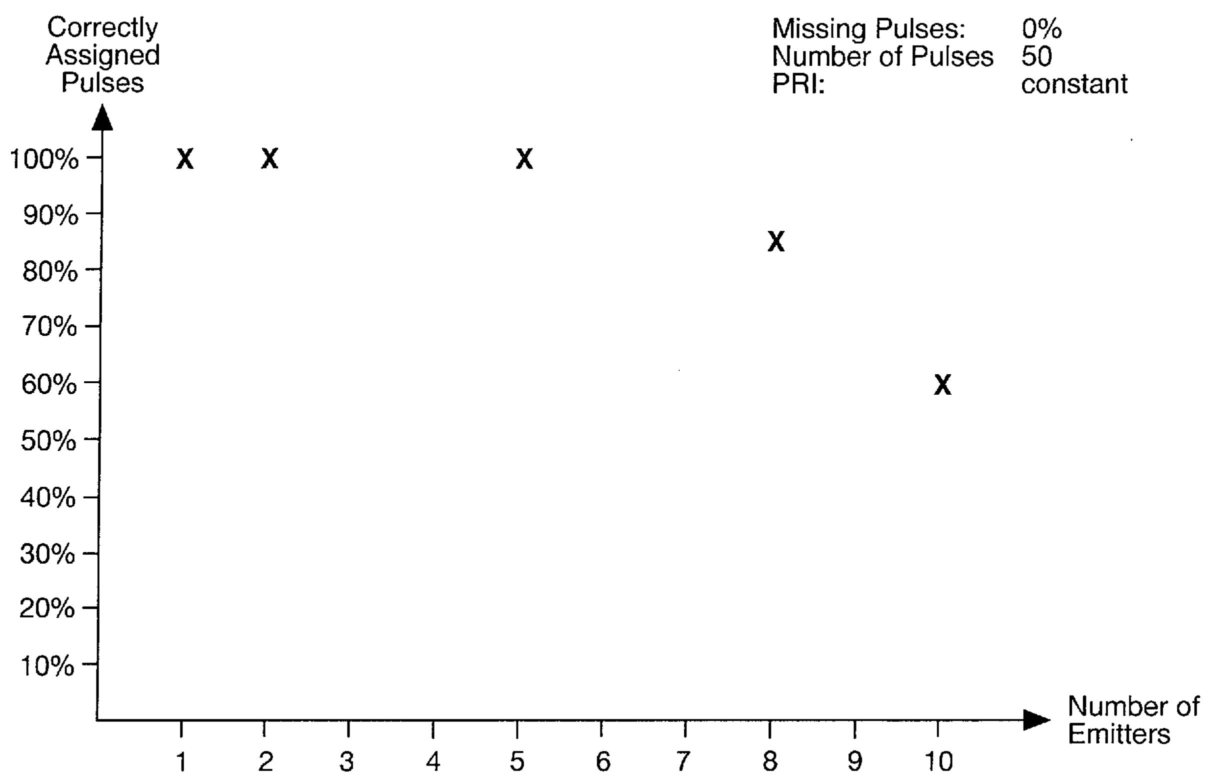


Figure 8: Performance vs. Number of Emitters

TRAITEMENTS AVANCES EN GUERRE ELECTRONIQUE
(ADVANCED PROCESSING IN ELECTRONIC WARFARE)

par

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1 - INTRODUCTION
Cet article présente un éclairage sur les récentes avancées des techniques de traitement d'information (Systèmes statistiques de reconnaissance, systèmes experts, apprentissage automatique Numérique Symbolique) dont la maturité permet d'envisager l'emploi pour des applications militaires opérationnelles intégrant des fonctions automatiques telles que l'identification de cibles, la planification d'actions.

Pour illustrer les principes de portée générale décrits, le cas concret de l'identification des émetteurs radars pour les systèmes de renseignement et les systèmes d'auto-protection est présenté.

2 - IDENTIFICATION D'EMETTEURS RADAR EN CONTRE-MESURES

2-1 Description de l'application
L'identification des émetteurs radars est un traitement critique pour l'efficacité des systèmes de contre-mesures aéroportés :
- dans le cadre de missions ELINT, la localisation précise des émetteurs sur le terrain doit être complétée par une identification qui renseigne sur le type de radar, les fonctions qui lui sont associées et ses caractéristiques techniques,
- dans le cadre de missions de suppression de défense ou pour assurer l'auto-protection des plateformes, l'identification en temps réel permet de mesurer la nature des menaces et leur degré d'engagement, ce qui permet de déclencher les actions a bon escient.

On notera que sur l'ensemble de ces missions, il est nécessaire d'assurer une cohérence très poussée des mesures réalisées par les différents capteurs et des processus de traitement de l'information mis en jeu sur l'ensemble de la chaîne, de recueil du renseignement d'origine électromagnétique (ROEM) d'une part, sur les dispositifs temps réel embarqués d'autre part.

Compte tenu de la richesse et de la diversité des informations traitées, l'identification des émetteurs radar constitue un champ privilégié d'investigation des nouvelles techniques de traitement de l'information décrites dans la suite.
Les exigences à prendre en compte pour traiter de manière satisfaisante le processus d'identification sont rappelées ci-dessous.

2-2 Principales exigences

2-2-1 Exigences d'ordre général
- Implémentation :
  Le processus d'identification doit être implémentable sur un calculateur fortement contraint en termes de ressources disponibles et/ou de temps de réaction.

- Prise en compte de l'incomplétude de l'information :
  Le processus d'identification doit être capable de prendre des décisions en ne possédant qu'une partie de l'information pertinente.
  Le système doit en effet, être robuste vis-à-vis de défauts d'information pouvant résulter d'une ambiance radioélectrique perturbée perçue par les capteurs.

- Pondération des décisions :
  Le processus d'identification doit être capable de quantifier la qualité de ses décisions et en particulier de juger de sa capacité ou non a décider (savoir que l'on ne sait pas).

- Détection des nouvelles classes :
  Il est important de pouvoir détecter l'apparition d'une nouvelle classe d'émetteur et de le prendre en compte dans le procédé d'identification.

- Adaptation du processus au contexte :
  Le choix de la mesure de ressemblance entre émissions radars est essentielle. Il s'agit de définir un "indice de similarité" entre émissions i.e. savoir si deux émissions sont proches ou si elles ne se ressemblent pas.
  Suivant les types de signaux que l'on compare, la mesure de ressemblance devra être définie en fonction du type d'émission et plus généralement de la classe d'origine à identifier.

2-2-2 Exigences propres à l'application
- Volume des données à traiter :
  Plusieurs centaines de radars peuvent être écoutés sur une mission, ils devront être associés a l'une des plusieurs milliers de classes potentielles.

- Complexité des motifs d'émission :
  Les radars modernes utilisent des modes de fonctionnement complexes pouvant comporter une ou plusieurs fréquences, aux valeurs déterministes ou aléatoires et émises simultanément ou successi-

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vement. De même pour les Périodes de Répétition des impulsions.

- Connaissance des motifs d'émission :
  Les radars sont identifiés à partir d'un catalogue de signatures. Ces bases de signatures sont renseignées et régulièrement mise à jour par des experts renseignement.
  La qualité de la base de signature va directement influencer le résultat de l'identification.
  La qualité du cycle de mise à jour de la bibliothèque de signatures contribue étroitement à la qualité de l'identification.

- Ambiguïtés intrinsèques :
  Certaines signatures se recouvrent partiellement. Il sera alors illusoire de tenter leur séparation dans la zone de recouvrement à partir de la seule connaissance de la signature.

- Identification à but décisionnel :
  Le processus d'identification peut être associé à une phase de décision : déclenchement d'une riposte (auto-protection), amélioration de la connaissance de certains types de signaux (renseignement) ...
  Dans ce cas le module d'identification, pour être efficace, devra prendre en compte ce but.

3 - DESCRIPTION DES PRINCIPES DES DIFFERENTES TECHNIQUES EMPLOYEES

3-1 Conditions d'application du processus d'identification

En préalable à l'application du processus d'identification, deux étapes doivent être franchies :

- La modélisation :
  La modélisation consiste à établir une représentation des phénomènes observés (trains d'impulsion) et à en ajuster les paramètres de telle façon que la ressemblance de comportement entre le phénomène observe et le modèle soit aussi parfaite que possible. C'est une démarche longue et délicate qui repose exclusivement sur la compréhension physique du phénomène observé. On déduit de cette étape les caractéristiques (les quelques paramètres qui résument le phénomène) du phénomène donc les capteurs de mesure et les étages de prétraitement de l'information.

- Le codage :
  Le codage vise généralement à établir une représentation des signaux la plus compacte possible, respectant certaines contraintes et tout en conservant un maximum d'informations utiles pour le problème à résoudre. Un codage astucieux dépendra donc obligatoirement du problème à résoudre.

  Il convient de noter à ce stade que ces deux étapes, sont la clé du succès de l'ensemble de l'opération et reposent essentiellement sur la connaissance humaine:

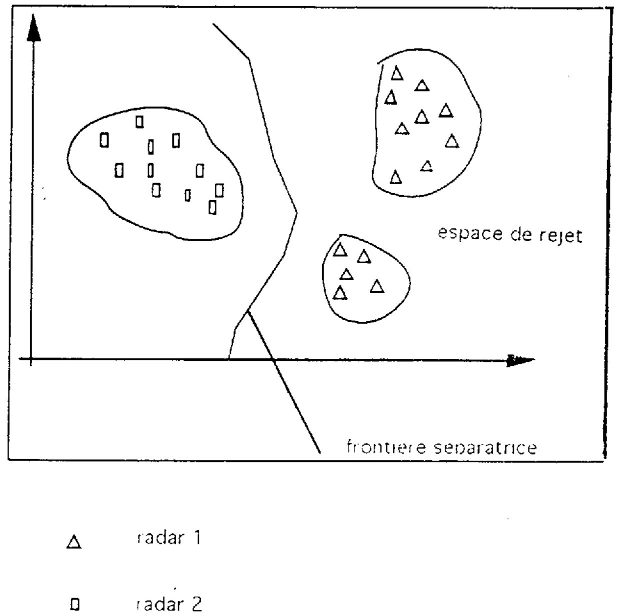
  . connaissance du fonctionnement du radar et son observabilité pour la modélisation,

  . connaissance des techniques de représentation de l'information permettant de produire une séparation des signaux radar, pour le codage.

  Pour réaliser une certaine optimisation de l'opération de codage, l'ordinateur constitue une aide utile permettant l'analyse et la visualisation des informations traitées.

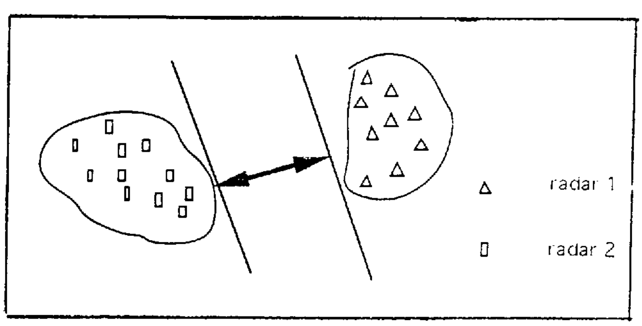
3-2 Les méthodes numériques

Dans le cas d'une analyse numérique, on représente une interception radar par un vecteur multidimensionnel dans l'espace de codage



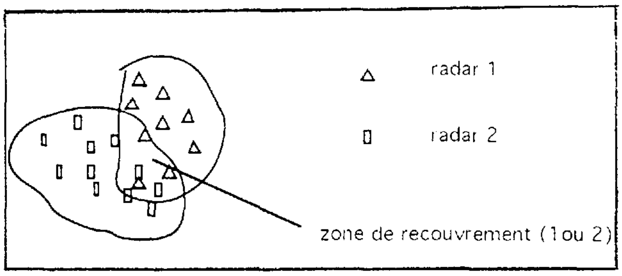
Les méthodes numériques ont pour objet :
- de découper l'espace de représentation en zones de décision,
- de traiter le rejet décisionnel (décider qu'une donnée ne correspond à aucun comportement connu),
- de donner la qualité de la décision.

La qualité du système dépendra :
- essentiellement de la séparation existante entre les classes à identifier dans l'espace de représentation,



- de la qualité (représentativité, exhaustivité, quantité) de l'information portée par les données qui vont permettre de calculer la fonction d'identification.

Lorsque deux classes se recouvrent dans l'espace de représentation il est intéressant d'étiqueter la zone (R1 ou R2). Un système central pourra éventuellement lever cette ambiguïté à partir d'autres informations. Dans le cas d'un système opérant en temps réel, les décisions pourront intégrer le maintien des deux hypothèses.



Les Réseaux neuronaux font partie de la classe des algorithmes numériques. La plupart des méthodes d'identification numériques existe en version neuronale. Leur intérêt majeur est principalement la standardisation qu'apporteront à terme les hardware spécialisés.

3-3 Les Systèmes Experts

Les recherches en intelligence artificielle ont été focalisées dans un premier temps autour du raisonnement formel et plus précisément autour des systèmes experts et moteurs d'inférences. A travers les systèmes experts, l'Intelligence Artificielle cherche à imiter l'un des aspects de l'intelligence humaine : la démarche logique.

L'apport essentiel de la technologie système expert réside dans des outils permettant de décrire la connaissance en juxtaposant des paquets de règle dans une base de règles, cette capacité autorisant des évolutions rapides de l'application. On parle de programmation déclarative.

Réalisé avec cette technologie le système expert d'identification de radars se présente comme une succession de traitements sur les données conditionnelles à la détection d'événements répertoriés.
Ainsi on commence une étape d'analyse du signal et de sa qualité.
Puis on sélectionne des candidats dans la bibliothèque de signatures.
On tente alors des mises en correspondance en faisant des hypothèses sur la qualité de certains paramètres. La méthode de comparaison peut alors être localement adapté au cas traité.

L'avantage est donc essentiellement dans :
- la capacité à enchaîner les éléments d'une démarche logique,
- la capacité à définir des cas et à associer à ces cas des opérateurs dépendant du contexte,
- la flexibilité liée à la programmation déclarative.

La qualité du système dépendra :
- de la qualité de l'expertise (exactitude, complétude),
- du taux de couverture des cas.

Les systèmes experts ont été appliqués avec succès par Thomson-CSF à des réalisations opérationnelles dans le domaine de l'ELINT.

L'adaptation de ces techniques à un contexte d'identification en temps réel, a donné lieu à une présentation lors du Symposium AGARD de 1986.

Les méthodes utilisées par Thomson-CSF font appel à des techniques de compilation de règles générant du code C ou ADA directement exécutable sur des machines standard.

3-4 Apprentissage Automatique Symbolique-Numérique

Comme leur nom le suggère ces techniques associent étroitement les principes de l'inférence logique et de l'inférence statistique.

Il s'agit avant tout de méthodes permettant l'analyse conjointe de l'information provenant des données et des connaissances expertes (règles expertes, mais également structuration des classes et des variables, connaissance des contextes ...).

L'Apprentissage Automatique Symbolique-Numérique intègre les connaissances expertes dans l'analyse numérique des données et automatise la détection et la synthèse de connaissances nouvelles apparaissant dans les données. Ces connaissances nouvelles sont par exemple :
- de nouvelles règles,
- de nouvelles classes inconnues jusqu'ici.

. Extraction et synthèse de règles d'identification :

Il ne s'agit pas de découvrir une connaissance qui n'existerait pas au départ dans les bases de connaissances du système (les nouvelles règles sont déduites des règles fournies en entrée) mais plutôt de reformuler le plus efficacement possible cette connaissance au fur et à mesure de la prise en compte de nouvelles connaissances acquises par l'observation des données.

Le système procède généralement à des reformulations successives du système de règles existant (utilisation de principes logiques étendant les principes experts) et à la sélection des règles les plus pertinentes vis-à-vis des données.

L'innovation réside principalement dans les capacités : utilisabilité immédiate de la connaissance produite, incrémentalité.

. Détection et prise en compte de nouvelles classes :

Le système réalisé est également capable de détecter l'apparition d'une nouvelle classe et de la prendre en compte immédiatement dans le procédé d'identification. Cette facilité sera illustrée par un exemple concret au paragraphe suivant.

On imagine aisément tout l'intérêt d'un tel apprentissage: par exemple un avion pénétrant détecte à distance de sécurité des modes de réponse radars à l'excitation de signaux brouilleurs; Le nouveau mode est détecté et inséré dans le programme d'identification; de plus la succession des différents modes est également acquise; les modes seront ensuite analysés pour envisager la contre-mesure optimale; lors d'une mission de pénétration ultérieure, l'avion attaquant pourra anticiper sur le comportement maintenant en partie connu de son adversaire.

4 - AVANTAGES ET INCONVENIENTS DES DIFFERENTES TECHNIQUES

4-1 Méthodes Numériques

- Bénéfices majeurs :
  . Exhaustivité de la couverture : tout l'espace de représentation est couvert par la décisionnelle, c'est à dire que toute donnée d'entrée produira un résultat attendu (répondant à certains critères; par exemple une donnée éloignée de toute classe connue ne conduira pas à une fausse information de classe).

  . Rapidité de remise à jour par exemple si les classes migrent (modification des paramètres de fonctionnement d'un mode). La décisionnelle est calculée à partir des données. Il suffit donc de réaliser le calcul sur les nouvelles données pour effectuer la mise à jour.

- Inconvénients :
  . Pas de prise en compte de la démarche conceptuelle (raisonner sur la stratégie de l'adversaire), cette prise en compte est possible avec des tests mais conduirait à un module très difficile à faire évoluer ou maintenir.

  . Contraintes fortes sur le codage : le codage doit assurer en entrée d'une méthode numérique une structure forte (généralement une structure d'espace vectoriel). La difficulté est alors souvent reportée sur le codage de l'information.

4-2 Systèmes Experts

- Bénéfices majeurs :
  Les systèmes symboliques sont très utiles quand :
  . L'expérience de résolution du problème est avant tout conceptuelle et ne peut être résumée par des chiffres. Il s'agit, par exemple d'une démarche stratégique ou d'un enchaînement logique (par exemple un enchaînement de modes radar).

  . Les données d'entrée sont incomplètes, fortement dépendantes de contextes et doivent être modifiées en fonction de la détection de certains événements.
  . Les données d'entrée ne sont pas directement consommables par une méthode numérique. On définira alors des critères de comparaison et des opérateurs adhoc suivant les différents contextes.

  . L'expérience de résolution du problème aura à évoluer dans le temps (modification et amélioration des stratégies). Dans ce cas la flexibilité de la programmation déclarative et la capacité d'explication du système permettent de satisfaire cette contrainte.

- Inconvénients :

  . Le coût du recueil et de la formalisation de la connaissance.

  . La difficulté pour assurer la cohérence des règles lors d'un recueil souvent incrémental (règles contradictoires par exemple).

  . La non exhaustivité de la couverture de l'espace de représentation. (Un cas entièrement nouveau peut produire un résultat inattendu).

  . La non prise en compte des connaissances apportées par les données.

4-3 Méthodes Symboliques Numériques

- Bénéfices majeurs :
  Les systèmes symboliques numériques présentent les avantages cumulés des deux types d'approches :

  . couverture de l'espace de représentation,

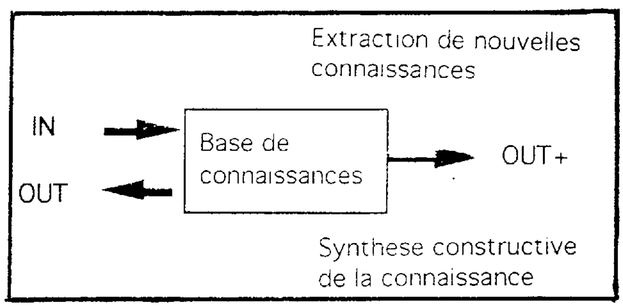
  . prise en compte de l'information contenue dans les données,

  . prises en compte de la connaissance experte,

  . évaluation statistique garantissant la robustesse.

Le gain résulte principalement dans la prise en compte simultanée des connaissances apportées par les données et des connaissances apportées sous forme de règles expertes.

L'apprentissage automatique réalise une synthèse constructive de la connaissance. Cette synthèse est incrémentale et permet donc de prendre en compte le caractère évolutif de l'information.



Dans un système traditionnel la connaissance est utilisée pour produire des résultats. (Schéma IN/OUT).

Dans un système d'apprentissage Numérique/Symbolique la connaissance est reformulée, restructurée. Il y a production d'un OUT +.

Un autre bénéficie important résulte des travaux de formalisation effectués. Ceci conduit à des bases de connaissances très structurées, cohérentes et à terme beaucoup plus maintenables et évolutives que les systèmes symboliques de première génération.

- Inconvénients :
  Les outils n'existent pas. Les temps de développement sont donc plus importants que pour les autres approches.

  Nécessité pour les concepteurs de posséder une double culture : connaissances approfondies en statistique et méthodes numériques; connaissances approfondies en IA symbolique.

5 - VALIDATION STATISTIQUE DE L'IDENTIFICATION

Quelle que soit la méthode retenue, il convient de disposer d'outils de validation statistiques permettront d'apprécier la performance de l'algorithme d'identification afin de garantir un niveau de performances en situation opérationnelle.

Le protocole classique de validation est de confronter le module d'identification à des données tests de classe connue. On mesure alors la réponse du système que l'on souhaite la plus proche possible du résultat attendu.

En pratique on peut utiliser des données simulées ou réelles qui vont pouvoir à loisir être distordues, bruitées, mélangées pour examiner la robustesse du système à toutes ces distorsions (bruit, données aberrantes, données manquantes, mélanges de deux classes ...).

5-1 Protocole de validation

Le protocole de validation repose sur l'analyse de matrices de confusions.

Le protocole est le suivant :
On dispose d'un ensemble de données test, dont on connaît l'identification et qui n'ont pas servi jusqu'ici à la construction de la procédure d'identification.

- Chaque donnée test est identifiée à l'une des classes connues.
- On peut alors comparer le résultat obtenu au résultat atteint.

La probabilité d'une erreur de classification est alors estimée par le taux de confusion.

- On définit conf (i, j) comme le nombre de données appartenant à la classe i identifiées à la classe j.

- On peut élaborer un taux de confusion global en réalisant une somme pondérée sur les confi (i, j) tenant compte de coûts décisionnels.

Un exemple de matrice de confusion est donnée ci-dessous:

Matrice 18x18:
Matrice de confusion en pourcentage:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	78							4	10		5							
1		99			1													
2			100															
3				83												17		
4				2	98													
5					3	97												
6							100											
7								96			1					3		
8	4								96									
9										100								
10	3							13			76		8					
11																		
12											2		95			3		
13														100				
14															50	50		
15																100		
16																20	80	
17													4			44		52

Erreur = 0.53 %
Ordre des radars:
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17

5-2 Qualité du résultat

La qualité du résultat observé est lié à cinq facteurs majeurs :
- La qualité des connaissances expertes introduites dans le système,
- La qualité de la base de signatures,
- L'exhaustivité des données d'apprentissage,
- La qualité des données (mesures) fournies au système,
- La qualité de conception de l'algorithmie.

Si l'utilisateur ne peut intervenir sur les deux derniers points, et difficilement sur le troisième il peut s'avérer très utile de le faire intervenir sur les deux premiers.

Il sera alors possible de très rapidement mettre à niveau le module d'identification et la base de signatures en fonction d'un théâtre opérationnel et des menaces découvertes lors des périodes de crise.

6 - AMELIORATIONS DU MECANISME D'IDENTIFICATION

Les améliorations décrites ont pour objet de procéder, à partir des résultats du protocole statistique de validation, à la mise en oeuvre de méthodes permettant d'accroître l'efficacité du processus d'identification.

Ces améliorations se déroulent selon trois étapes :
- la restructuration de la matrice de confusion,
- la focalisation d'attention,
- l'amélioration locale.

6-1 Restructuration de la matrice de confusion

Le nombre important des classes d'émissions impose la mise en oeuvre de méthodes de restructuration des matrices dans le but :
- d'accroître leur lisibilité,
- de focaliser l'algorithme ou l'expert humain sur les cas résistant à l'analyse, c'est à dire les zones de l'espace de représentation où l'information disponible n'est pas suffisante pour discriminer les classes (on suppose savoir travailler efficacement au niveau de l'algorithme).

La restructuration de la matrice de confusion consiste à regrouper les classes qui se recouvrent dans l'espace de représentation. Ces classes recouvrantes induisent des taux de confusion élevée. On obtient alors une matrice dont les valeurs diagonales sont élevés et les valeurs hors diagonale faibles.

6-2 Focalisation d'attention

Une fois cette restructuration effectuée on distingue différents cas :
- Les émetteurs qui sont quasiment toujours correctement identifiés.
- Des blocs de radars se recouvrant. Il faudra alors examiner le problème pour améliorer l'identification sur le bloc correspondant, ie la zone locale de l'espace de représentation,
- Des radars attracteurs. Il s'agit généralement de radar dont les signatures sont mal spécifiées (l'opérateur a rentré par méconnaissance des fourchettes larges).

L'attention de l'opérateur est focalisée sur ces différents cas et il peut alors apporter un remède localement efficace.

6-3 Amélioration locale
La procédure consiste à remonter aux différentes données présentes dans la zone locale posant problème (données appartenant aux classes en présence) et en observant ces données à compléter les données en rajoutant localement pertinente : soit un descripteur numérique, soit une règle experte.

Pour un système expert cela consistera au rajout d'une règle locale (qui n'aura d'intérêt que pour les classes en présence localement).

Pour un système numérique cela consistera à augmenter la description d'un paramètre localement pertinent.

Pour un système numérique/symbolique cela consistera à explorer un catalogue de solutions potentielles, à sélectionner les solutions localement pertinentes et à les introduire automatiquement dans le procédé.

Ces recherches automatiques sont particulièrement rapides dès lors qu'elle sont conduites localement. Il n'y alors jamais de problème pour assurer des cohérences locales de règles.

Les problèmes rencontrés sur les temps de calcul ou les cohérences des bases de règle sont souvent liées au fait que ces problèmes sont traités globalement alors qu'il relèvent d'une problématique locale (l'identification entre la classe 1 et 2 n'a rien à voir avec l'identification de la classe 3 qui se situe dans une autre partie de l'espace de représentation).

6-4 Illustration du mécanisme
L'exemple de la planche A présente une petite portion d'une matrice de confusion, avant (A1) et après restructuration (A2).

Il faut noter que la matrice de départ (A1) est déjà structurée en fonction de la proximité des classes dans l'espace de représentation (par exemple classement par ordre croissant des fréquences).

Le fait d'obtenir un classement différent des radars en A2 démontre pratiquement que la similitude entre classes n'est pas une simple distance euclidienne dans l'espace de représentation.

L'opérateur dispose en outre de fonctions lui permettant de calculer les taux de recouvrement entre signatures prototypiques dans l'espace de représentation.

On observe en (A3) (A2) les différentes typologies de problèmes rencontrées :
- classe diffuse (radar attracteur)
- zone confuse,
- radars identifiés à 100%.

Les différents procédés d'amélioration sont alors les suivants (A4) :
- pour les classes bien identifiées le résultat est atteint,
- pour les autres cas il convient de rechercher tout d'abord si le problème ne vient pas de la base de signatures par un examen des taux de recouvrement; dans ce cas l'opérateur pourra alors :
  . soit privilégier localement une classe correspondant à une menace de forte nocivité,
  . soit réétiqueter la zone (R1 ou R2 ou R3) dans la zone de recouvrement,
  . soit corriger les valeurs définissant les signatures prototypiques.
- Si le problème n'est pas lié à une ambiguïté intrinsèque de la base de signatures, l'expert "renseignement" va alors devoir enrichir la description locale du problème et apporter l'information permettant une bonne discrimination locale. Dans le cas d'un système expert il s'agira par exemple de créer une règle d'exception. Dans le cas d'un système numérique on pourra ajouter un descripteur pertinent, (par exemple si l'on sait que certains radars de la zone ont des modes à PRI/LI constant il suffira de coder un nouveau paramètre local PRI/LI). L'expert renseignement est aidé dans cette tache par des outils de visualisation des données de la zone considérée, et des outils de saisie et de contrôle des connaissances introduites.
  L'outil permet des gains de temps d'autant plus important par rapport à des méthodes classiques (100 à 1000) que les bases de données mises en jeu sont de grande dimension.

6-5 Intérêt pratique
La technique présentée est particulièrement efficace pour l'amélioration itérative des moyennes et grandes bases de signatures :
- La mise à jour est rapide (focalisation d'attention), comparativement aux procédés courants dans le domaine.
- La recherche de descripteurs pertinents ou de règles locales peut s'effectuer automatiquement sans explosion combinatoire puisqu'il s'agit d'un problème local.
- La complexité des discriminateurs est locale. Ces discriminateurs garantissent une grande reproductibilité des résultats en situation d'emploi opérationnel.

Le cycle de mise à jour du système d'identification (module décisionnel et bases de signatures) obtenu est rapide, cohérent, fiable.

7 - LE MODULE D'IDENTIFICATION NUMERIQUE-SYMBOLIQUE TEMPS REEL

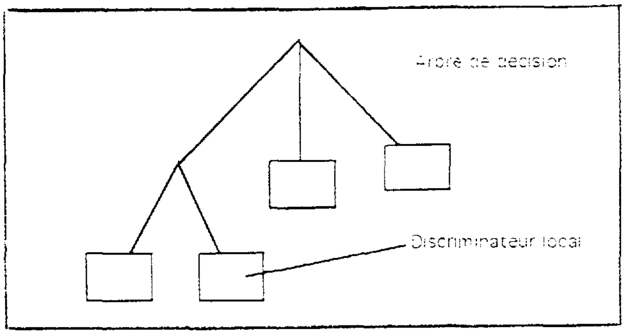
Ce paragraphe décrit un principe de préparation d'une application temps réel.

Contrairement aux approches classiques qui n'agissent que sur la structure des données sur lesquelles opère un algorithme figé, il s'agit ici de générer automatiquement le module d'identification, en fonction des données sur lesquelles il est censé opérer, le module généré étant en outre capable d'apprendre les classes de signaux non prévues, puis de les reconnaître.

Le résultat en est un algorithme d'identification optimisé en termes :
- de rapidité d'exécution,,
- de capacité de séparation des signaux,

et qui, embarqué, bénéficie du maximum d'expertise acquise en temps différé.

La structure de l'algorithme généré est décrite ci-dessous.



Dans chaque zone de l'espace un discriminateur local a été synthétisé.

Cette synthèse est réalisée par :
- sélection dans le catalogue général des connaissances expertes des règles localement pertinentes,
- génération de règles locales cohérentes résolvant le problème,
- validation automatique du résultat.

Le procédé présente les avantages principaux suivants :
- localité des décisionnelles (adaptation au contexte),
- maîtrise de l'explosion combinatoire (la mise en cohérence d'une base de règles, la génération de nouvelles règles par reformulation sont des problèmes exponentiels) grâce à la localité,
- robustesse et qualification des décisions,
- capacité d'apprentissage (nouvelles règles et nouvelles classes).

Le système décrit tient compte de façon intégrée et cohérente des éléments d'information suivants :
- une base de données des interceptions réalisées,
- une base de données des signatures,
- une base des connaissances expertes.

La fonction résultante à la capacité :
- de reconnaître les modes radars décrits par une signature ou des interceptions antérieures,
- de détecter en temps-réel l'apparition d'un nouveau mode radar et de le distinguer d'une anomalie ponctuelle de mesure,
- de mettre à jour le procédé d'identification soit en temps réel soit si cela est compatible de la fonction à assurer en temps différé.

Les principaux avantages sont :
- la capacité à traiter localement et donc de façon adaptée les différentes classes cibles,
- la capacité à tenir compte simultanément des informations décrites sous forme symbolique ou numérique,
- l'aptitude à intégrer les règles expertes au niveau local,
- la faculté à s'adapter au bruit,
- la capacité à apprendre de nouvelles classes et à les prendre en compte dans le discriminateur,
- la capacité à apprendre de nouvelles règles et à les prendre en compte dans le discriminateur.

Cet algorithme a été conçu afin de prendre en compte les spécificités de l'application d'identification des radars.

Il peut cependant s'appliquer de la même façon à tout problème de génération automatique d'une fonction d'identification, lorsque l'on dispose d'une base de signatures prototypiques, d'un ensemble d'individus d'apprentissage et que l'on désire maintenir à jour à la fois la fonction d'identification et la base de signatures prototypiques.

8 - APPLICATIONS MILITAIRES POTENTIELLES

Les systèmes militaires futurs intégreront des fonctions d'aide, de décision "intelligentes" au sens où elles produisent ces décisions dans un environnement éminemment variable.

Parmi ces systèmes, dans le domaine de la guerre électronique, on peut citer :

- les nouveaux systèmes de surveillance du champ de bataille qui devront détecter, identifier et localiser des cibles de plus en plus discrètes et nombreuses,

- les systèmes de renseignement qui seront confrontés à des signaux de plus en plus complexes et fugitifs nécessitant un recueil dynamique et focalisé de l'information,

- les aides au pilote d'avion d'arme comme le choix des modes d'actions pour contrer les menaces,

- les systèmes de renseignement satellitaires qui nécessitent la mise au point de très grande bases de signatures, fortement structurées.

La méthode numérique-symbolique décrite permet de satisfaire les exigences d'optimisation du processus d'identification au problème à traiter, en maintenant une cohérence étroite avec l'expertise acquise lors du recueil d'informations.

Figure 1

Matrice initiale:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	78							4	10		8							
1		99			1													
2			100															
3				83												17		
4				2	98													
5					3	97												
6							100											
7								96			1					3		
8	4								96									
9										100								
10	3							13			76		8					
11																		
12											2		95			3		
13														100				
14															50	50		
15																100		
16																20	80	
17													4			44		52

Figure 2

Matrice finale:

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
0	99		1															
1		97	3															
2			98	2														
3				83		17												
4					50	50												
5						100												
6						44	52		4									
7						20		80										
8						3			95				2					
9										78	10	4	8					
10										4	96							
11						3						96	1					
12									8	3		13	76					
13														100				
14															100			
15																100		
16																	100	
17																		

Ordre final des radars:
1 5 4 3 14 15 17 16 12 0 8 7 10 2 6 9 13 11

Figure 3

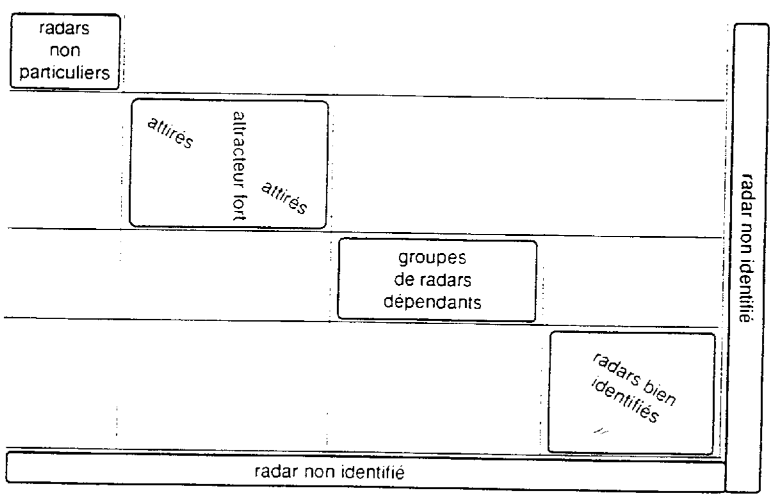
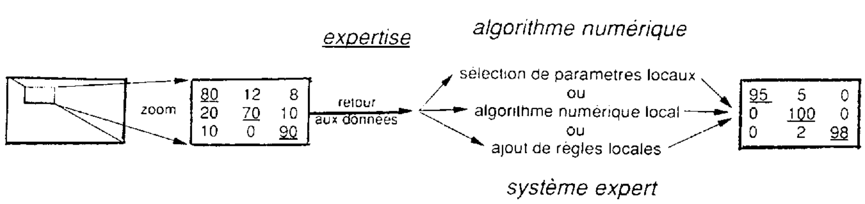


Figure 4



→ *discrimination locale (adaptation locale) = meilleures performances*

Planche A

HIGH TEMPERATURE SUPERCONDUCTIVITY (HTS) AND ITS ROLE IN ELECTRONICS WARFARE

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SUMMARY

This decade, the quest for materials exhibiting the property of superconductivity at temperatures far above absolute zero has yielded astonishing results. First, varieties of yttrium-barium-copper-oxide ceramics, cooled with liquid nitrogen at 77 degrees Kelvin were produced and more recently, other ceramics capable of mantaining their superconductive properties at temperatures like 130 degrees K are opening the way to the routine design of a growing family of electronic communication components, which complement the pioneer HTS achievements in ultra powerful motors, electromagnets, and other equipment of stationary nature.

The debut of HTS components in the RF field was in the design of a variety of microwave components, whose frequency-dicatated small size make them easy to pack in a cryogenics environment. With the experimental evidence that AC conductivity increases steadiliy as one decreases the value of the operating frequency it is evident that this phenomenon has to be exploited in the lower frequency bands (MF, HF and VHF). Receivers with superconducting components will have impressive sensitivities; HTS transmitter components are allowing higher ERP'S at savings in volume and weight. Modern Army jamming systems will systematically suffer a metamorphosis as a result of the research in this field, pioneered at CECOM IEWD in Warrenton, Virginia.

1.0 HISTORICAL INTRODUCTION

On July 10 1908, Dr. Heike K. Onnes, professor of experimental Physics at the University of Leyden in The Netherlands succeeded to liquefy helium for the first time. Helium liquefies at 4.2 degrees K under standard atmospheric pressure. This rare product was used by Onnes to investigate resistivities of various metals in this temperature regime. Earlier experiments had shown that by lowering the temperature of conductors, their DC resistivities decreased, and by extrapolation they would vanish at the (unreachable) absolute zero. In Onnes' experiments an unexpected result was observed: the resistivity of mercury suddenly became zero as it was being cooled by helium at 4.2 degrees K. After ascertaining that there were no short circuits and that the measurements were accurate, he tested other metals; among them Indium, Tin and Lead. Their critical temperatures (transition to the superconducting state) were respectively 3.4, 3.7 and 7.2 degrees Kelvin (Ref 2).

Dr. Onnes received the Nobel award in Physics in 1913. Large scale commercial applications of superconductivity were soon envisioned. At that time it was not known that neither external magnetic fields exceeding a critical value H_c, large throughput current, nor power values and high frequencies, as well as temperatures above a critical value T_c would quench the effect of superconductivity. Accordingly, "quenching" extended to many of these preliminary envisions of applications, making it necessary to re-examine soberly the potential applications of low temperature superconductivity.

In 1933, Walter Meissner and Robert Ochsenfeld, in Germany, discovered that an external magnetic flux of moderate amplitude was not only excluded from entering a superconductor (diamagnetism), but it was also dynamically expelled from its interior (at some expense of energy). This experience, the "Meissner Effect" demonstrated that superconductivity is a magnetic phenomenon and is used as a test on whether a material is superconductive. In 1952, Alexei Abrisokov, in what was called the Soviet Union, produced a new family of materials: Type II superconductors. These types can conduct large currents and expel even larger values of magnetic fields, therefore they can be used to make powerful electromagnets which do not quench to the normal state under normal use conditions.

HTS, or superconductors with high critical temperature (T_c) were first reported in April 1986 by the Zurich IBM group led by Georg Bednorz, who produced a Lanthanum-Barium-Copper-Oxide with a T_c of 30 degrees K. The modern types of HTS materials were arrived at in Huntsville, Alabama in January, 1987 by Wu, Torng and Ashburn, who were seeking a substitute for Barium in La-Ba-Cu-O. This quest led to the discovery of Yttrium-Barium Copper Oxide or $Y_1 Ba_2 Cu_3 O_7$. This easily produced ceramic has a T_c of 90° K (Fig 1), so liquid nitrogen is more than sufficient to cool it to the superconductive state. On March 18, 1987, the American Physical society held a large meeting in New York City where the new ceramics were introduced to the public and scientific communities. Presently HTS materials make several families, each composed of various proportions of the elements

Presented at an AGARD Meeting on 'Challenge of Future EW System Design', October, 1993.

Y-Ba-Cu-O, (LaSr)-Cu-O, Bi-Sr-Ca-Cu-O and Tl-Ba-Ca-Cu-O.

2.0 IMPORTANT SUPERCONDUCTIVITY PHENOMENA

The superconductive state's most notable macroscopic features are zero DC and very low AC resistivities as well as imposing near perfect diamagnetism under moderate magnetic fields. The last property, the Meissner Effect culminates with the expulsion of magnetic fields from the interior of the material, except for a thin region at the surface, where a screening current is established to cancel the magnetic field in the interior.

In the superconductive state electrons associate in loose pairs (Cooper Pairs) separated by an interval called coherence length and interact with the lattice through phonon interactions (lattice vibrations). In the DC case and with a perfect lattice, the Cooper pairs flow coherently along the crystals in the same plane without interruption or loss. In the AC case, the fact that electrons have nonzero momentum and kinetic energy, prevents the electrons from reacting instantaneously to the AC electric field, so this lag creates a secondary normal electric field along the surface of the conductor which in turn will drive normal (single) electrons producing ohmic loss. The theory explaining this well understood phenomenon is referred to as the two fluid model (Ref 1).

At frequencies higher than the energy gap value divided by Planck's constant, the extra energy absorbed by the material excites the electrons so that the electron pairs dissociate and the electrons become normal, thus quenching the superconductive state.

High current densities exceeding a critical value J_c can also quench the superconductive process. This critical current is a function of the temperature, the crystal geometry and the state of the material, and depends too on whether the magnetic field produced by the surface current exceeds the material's H_c.

If an applied magnetic field exceeds the H_c value, a screening current that prevents H from developing inside the material, would require a large amount of energy to be established. If the energy required to produce the screening current is larger than the energy required to transition to its normal state, the system will follow the least energy demanding path (reduce its energy) and the material will become normal.

The two known types of superconductors (Types I and II) have respectively one and two H_c values. In type I superconductors, if $H > H_c$, then H penetrates the material completely, quenching it. In type II materials, which have an H_c low and an H_c high, two phenomena can occur: either $H < H_c$ low, or $H > H_c$ high; then there is respectively no flux penetration at all, or on the other hand there will be quenching as in type I superconductors. Finally, for H values between both H_c's of type II, the H field penetrates in a partial and organized way, forming a "mixed state" of pinning points or vortices whose radii are comparable to the coherence length. These vortices are distributed in regular intervals within the otherwise superconductive material. As H approaches H_c high, these vortices group together more densely until they leave no voids in the superconductor material and becomes normal. Modern HTS materials were discovered in 1987 by Wu et. al. belongs to the Type II class.

The mixed state of Type II superconductors allows for much higher critical current densities and magnetic field strengths. This difference can be as high as three orders of magnitude.

3.0 CHARACTERISTICS OF HIGH TEMPERATURE SUPERCONDUCTOR MATERIALS

Modern HTS materials are ceramics composed of copper oxides and non-metallic chemical elements, as mentioned in Section 1.0. All HTS material belong to the Type II class. Indeed, the most notable difference between Types I and II is the lack in constituents of common metallic conductors as in Type II.

The crystal structure of an HTS material is similar to a "perovskite" unit cell (Fig 2) where a metal anion lies at the center of a cube of cations, surrounded by an octahedral configuration of oxygen atoms. In these unit cells, the Cu-O groups are strongly linked and all lay in two planes in each cell. These planes correspond to the a-b plane of the cell and it is only in these planes that the conduction phenomenon occurs. Additionally, the zero DC or low AC resistivities occur at the surface of the sample, decaying exponentially as one penetrates into the material. Based on these facts surface resistivity (R_S) is a significant parameter of HTS materials. These anisotropies of HTS materials have to be taken into consideration in the design of superconductive electronics components.

The three structural types of HTS materials in production today are bulk, thin films and thick films. Bulk HTS materials are free standing poly or single crystals made by sintering, i.e., extruding a hot composite of Yttrium Oxide, Barium Carbonate and Copper Oxide in powder form, combined with a thermoplastic binder. Then it is heated and shaped into a continuous monofilament called green fiber. Green fibers can be shaped into desired forms such as a straight line with a determined cross section, helices, etc. After sintering, the wire is "melt textured", in other words, it is zone-wise molten under a constant magnetic field and made to recrystallize into either one very long crystal or a collection of parallel crystals with undiscernible grain boundaries. Today's melt textured bulk materials can withstand current densities of 20,000 Amp/cm as well as magnetic fields of 8 Teslas (80,000 Gauss) without quenching.

Thin films are made by deposition onto substrates like Aluminum oxide (sapphire), lanthanum aluminate, strontium titanate, etc, by processes like laser ablation, off-axis RF magnetron sputtering or electrophoretic deposition. They can be deposited into single or poly-crystals, where the single crystal or epitaxial format offers the best values of surface resistivity and critical temperature. For several years thin films had the lowest available values of surface resistivity, especially at VHF and UHF frequencies. Today, bulk and thin films are in even competition. Thick films are the newest and hitherto less tested materials. They have properties common to both bulk and thin films (Fig 3, Table 1).

Nonlinear RF effects like intermodulation, power dependence degradation, etc are being tested by several private industries and universities in addition to the US Naval Research Laboratory (Ref 10). The tests are designed to qualify the various samples in terms of the possibility of production of unwanted power dependence effects and non linear mechanisms of signal degradation.

4.0 COMMUNICATIONS AND ELECTRONICS COUNTERMEASURES APPLICATIONS OF HTS MATERIALS

Since the onset of high temperature superconductivity, the world engineering community in general has been eagerly looking for new applications provided by high temperature superconductivity to improve the performance of electrical and electronic equipment.

The dawn of RF use of HTS materials was in thin film technology. which was applied into microwave components. Two important examples of RF applications of HTS in the microwave frequency world are microstrip and stripline filters, resonators and distributed element bandpass filters. These devices can greatly reduce system noise temperature and improve the stability of a signal. An inherent asset of HTS filters is their very high Q values, so they can satisfactorily replace cavity filters. At this time, thin film technology seems best suited for the production of these devices of planar geometry.

The most important RF application envisioned for HTS devices is for the front end of HF, VHF and UHF transmitting and receiving equipment. To this date, these front end devices are microwave antenna elements, impedance matching networks, delay lines, filters, resonators, signal distribution (Butler) matrices, etc. (Figs 7, 8, 9; Ref 6).

Consider for example delay lines. These devices can be used in military ESM applications such as in signal processing (calculating fast Fourier transforms, correlation functions and other analogical calculations) where the value of a signal is needed at a shifted (delayed) time. The HTS delay line's advantage resides in the fact that conventional delay lines have unbearable losses, while their tiny HTS counterparts can do the same job without signal losses.

The proven HTS advantage of 4 to 6 order of magnitude reduction in surface resistance of bulk materials might lead to miniaturized HF antennas with a two orders of magnitude size reduction. The easily attained high critical current values of lO,OOOA/cm2 under high magnetic fields makes possible high power transmit and jamming applications. HTS material have further EW applications in beam formers and RF memories for jammers. The advent of high reliability small size closed cycle cryogenic coolers such as the Oxford Systems cooler employed in the NRL Superconductor Space Experiment with a three-year lifetime has removed many of the reliability and logistic objections to devices requiring cryogenic support (Ref 7).

HTS helical transmission and delay lines are a particularly attractive component for reducing the size of HF antenna systems. HTSC materials allow the dimensions of helical transmission lines and resonators to be reduced by a factor of over 100. For instance 1/2 wavelength lines at 15 MHz are only 10 cm (4 in.) long. Dielectric loading of HTSC delay lines will provide an extra other order of magnitude reduction in delay line length. These lines can be used to make lossless multistub matching networks for small antennas, lossless channelized filter banks frequencies, and a number of other components which will greatly reduce the size of and increase the performance of HF antenna systems.

4.1 ROLE OF HTS IN ELECTRICALLY SMALL ANTENNAS

The reduction of antenna size in the HF frequency range is important to improve mobility and decrease observability of HF systems. Superconductivity can contribute to this goal in at least three distinct ways:

A. Lossless filters can be inserted between the antenna and the high impedance amplifier in electrically small antenna applications to reduce the dynamic range requirements and improve system performance

B. Optimal bandwidth antenna elements offer a factor of 10 more bandwidth than an equivalent size dipole can be realized with superconductors

C. Slow wave superconducting helical delay lines make miniature lossless stub matching networks for tuned electrically small antenna elements.

The simplest way to obtain a large bandwidth with a receiving miniaturized antenna is to operate in an essentially unmatched condition with a high impedance amplifier directly mounted on the antenna. Channelizing the receiver with sharp cutoff filters would solve any dynamic range problem for this receiver configuration. However, existing filters have too much insertion loss in an already compromised signal to noise ratio situation. However superconducting filters have the combination of high Q and essentially low insertion loss that is required to solve the HF dynamic range problem.

4.2 PRACTICAL ASPECTS OF USING MINIATURIZED HTS ANTENNAS WITH MATCHED LOADS

Superconductors can also be employed to make electrically small antennas for both transmit and receive applications. In addition, applications such as DF are of interest which can utilize more sensitivity than HF radar or communications receivers because of the differential mode of DF operation. Antennas operated with matched loads are required for these applications. Two basic problems arise with conventional electrically small matched antennas. First, the bandwidth becomes impractically small as the electrical size of the antenna is reduced. Second, the antenna and especially the matching network dissipates much of the incident power as the electrical size of the antenna is reduced. Superconductivity can solve both of these problems.

Recent evaluations of antenna applications of HTS have come to the conclusion that there is no efficiency benefit in making the antenna itself out of superconductors. This is certainly true for dipoles if only the radiation properties are considered. However, compared to the dipole antenna, a factor of 10 in bandwidth, can be achieved by using a more complex antenna. Bandwidth is the most serious penalty which must be overcome to achieve a practical electrically small antenna. These optimal bandwidth antennas have ohmic losses that rival the radiation resistance resulting in as much power dissipated ohmically in the antenna as it is radiated. In addition, the heat loss from the cryogenic region to the outside world via an exposed antenna is not tolerable from a systems point of view. In transmitter applications, the ohmic heat dissipation of even a small fraction of the total power in the antenna has a great effect on cryogenic requirements. Therefore, from a practical point of view the antenna element itself must be superconducting if it is inside the cryogenic region.

The major source of inefficiency in small antennas is dissipation in the matching networks. The large size of the required networks when they are made with normal metal conductors is also a problem. Superconducting slow wave delay lines solve both of these deficiencies. In addition, the superconducting circuits (an array of staggered tuned antennas) needed to achieve a usable bandwidth can be engineered without incurring intolerable losses.

In a research project between the US Army and Foster Miller, Inc. of Waltham MA., the most challenging part of that program has been the construction of melt textured, single crystal HTS coils for the slow wave transmission line needed for the miniature matching stubs. The solution of this question is a major technical accomplishment and forms a first step in the application of HTS to reduction of antenna sizes in the HF frequency regime. Cera Nova Co., the bulk type HTS ceramics producer, has mare and tested melt textured wires with a critical current of 50,000 Amp/cm2. Melt textured wires are an improvement of sintered wires in which their crystal morphologies have been restructured to form one continuous crystal. Although each sintered crystal is a true superconductor a wire made of sintered material will not work because the inter-crystal boundaries act as resistance mechanisms; therefore a single crystal morphology is imperative.

4.3 SIZE REDUCTION GOALS

HTS materials provide an opportunity to reduce the length of a matched dipole antenna element by a factor of about 100 without losing efficiency. In calculating the required electrical length of a tuned antenna, it must be remembered that the length of the matching network is part of the total antenna's electrical length, therefore the matching network for HF electrically small antennas adds an additional length which is coincidentally about the same length as the antenna itself. Recently, Foster Miller concluded analytically that delay lines with delay values of 2500 n-sec per meter can be built.

Small HF array structures are being envisioned for a number of applications such as mobile direction finder systems. It will soon be possible to produce individual antenna elements coupled to signal conditioning elements weighing less than 35 Kg. These antennas could be deployed by two soldiers from the back of a small vehicle for large base line array and connected with fiberoptic cable to a central processing unit in the vehicle. Such a concept would greatly reduce the logistic complexity of deploying sensitive long base line arrays.

4.4 HTS BULK WIRE VERSUS THIN FILM TECHNOLOGY

One objective of the mentioned Foster Miller program was to apply basic HTS technology to the development of a two element DF array. The key element in application of HTS to HF antenna array systems is to build slow wave structures which permit size reduction. Most of the effort in HTS small antennas has focused on traditional HTS thin film microwave transmission lines such as microstrip lines with propagation velocities nearly equal to that of light. The theme of the thin film studies was to compare the losses of superconductive and standard copper transmission line structures and demonstrate greater efficiency with HTS.

In the HF regime much of the reduction in resistivity resulting from HTS can be used to achieve size reduction and improving efficiency although the latter subject is still an open issue.

As Fig 3 illustrates, HTS bulk ceramic technology is most effective at the lower HF frequencies and perhaps even lower frequencies The materials already developed have sufficient advantage compared to normal metals in the HF region to support applications. The bulk technology is suited for the fabrication of large structures (order of O.lm) needed after size reduction (in the HF regime). Since the bulk wire structures are stand alone mechanical structures, they can be combined with dielectric material optimized for the specific application. The wire technology becomes less useful as the frequency of application increases beyond 300 MHz. In that new regime coil fabrication is difficult due to the small size of the circuits and the reduction in surface resistance of HTS ceramics relative to that of copper is no longer as great.

5.0 OTHER ROLES OF HTS IN ELECTRONICS WARFARE

The Electronics Countermeasures Laboratory of CECOM-IEWD's Research and Technology Division is engaged in the development of effective, state of the art communications electronic warfare SIGINT equipment. This effort includes the conceptualization, development and testing of complete jamming systems designed to perform target signal reception and analysis and subsequent jamming at frequencies ranking from HF to UHF.

HTS technology has applications in many and diverse components of EW jamming hardware. The receiver and the transmitter of a jammer contain analogue and digital signal processing and power handling electronics which will benefit significantly from HTS and can be easily packaged in a cryogenics environment. With smaller and lighter electronic components of negligible resistivity one expects immediate benefits on effective jamming power, speed, bandwidth, resolution and dynamic range.

The design of components of a receiving/transmitting antenna of a jammer will also dramatically improve with superconductivity. It has been proven practically that the coupler of a transmitting antenna is able to handle previously forbidden power levels when its components are made superconductive. Delay lines used in a powerful pattern-steering array jamming antenna as well as in a precise direction finding antenna can be significantly improved with HTS. In the case of jamming the advantage is more critical since ordinary, non superconductive delay lines are impedingly large, heavy and highly inefficient for they dissipate most of the signal into ohmic power.

Future milestones in this planned technology are integrating components into systems, studying the feasibility of constructing a complex jamming subsystem, interfacing such components to existing hardware and producing HTS analogue signal processing networks and related software.

Research has demonstrated that lossless filters can be inserted between the antenna and the high impedance amplifier in electrically small antennas to reduce dynamic range requirements and improve system performance. Additionally, with the use of lossless filters bandwidth can be improved by a factor of 10 over an equivalent size ordinary antenna. Finally, it was proven that HTS helical delay lines make excellent miniature lossless stub matching networks for electrically small tuned antenna elements.

An ongoing US Army contract with TRW Incorporated of San Diego, CA, recently demonstrated analytically how it is possible to enhance radiation efficiency of HF antennas for ground based EW applications. Impedance matching networks are made so that the sum of the electrical lengths of the matching inductor and the antenna's radiator totals one quarter wavelength at the chosen frequency. With such premises it is recommendable to make them of superconductive bulk wire. The only practical deficiency in this scheme is that the tuner's ohmic losses Rt and ground return losses Rg do not contribute to improve the value of the radiation efficiency N.

Efficiency N of a system is defined as the ratio of power output to power input. It follows then that

$$N = \frac{Rr}{(Rg + Rn + Rr)}$$

Where Rg is the ground resistance, Rn is the impedance matching network's resistance and Rr is the antenna's radiation resistance.

Antenna efficiency can be increased by HTS techniques from 25% to 80%, depending on the value of ground return losses. Although most ohmic losses will occur in the inductor, it is inexpensive to pack the entire matching network in a cryogenic environment for enhanced results.

In a multi-threat ECM environment, the above arguments lead us to conclude that since high Q values limit instantaneous bandwidth, the means of tuning the antenna is a vital necessity. At the present there are two ways of satisfying this necessity: The first approach is a rapid antenna tuning device for matching impedances at a hopper's rate. This is now a reality with the agile coupler designed by American Laboratories of Lansdale, PA. It makes use of rapid, high power switches to select the correct values of L and C. A 10 meter antenna operating at one (1.0) MHz can thus radiate at 63% efficiency. A superconductive version of this rapid coupler is now being designed under contract. The second approach is Harris Co. and Foster Miller's folded dipole antenna (Fig. 13) which incorporates a superconductive half wave delay line which has sufficient number of resonances (eigenvalues of frequency) in the HF range to produce a suitable number of pure resistive impedances to provide a quasi-continuous matched impedance throughout the HF range.

Hypres Incorporated of New York has been working in low and high temperature superconductive analogue to digital converters and other communication systems. One of them is the production of low noise amplifiers and electrically small, low noise (non HF) antennas, together with the integration of HTS components into monolithic substrates with significant cost reduction.

Another project by Hypres Co. is an HTS multi-port mode forming network for an array antenna. The network is configured in the shape of a matrix and it has been developed and tested. This is referred to as a Shelton-Butler matrix, it consists of hybrids and fixed phase filters. Together with Foster Miller, a tunable circular 4-element array antenna for DF uses has been conceptualized.

The research of the US Army Sigint EW applications and related contracts described above is in an active and dynamic status at the time of the publication of this article. This review is by no means exhaustive. Changes and additions will follow as this emerging technology gains further momentum.

6.0 RECOMMENDED BIBLIOGRAPHY

This article discusses only selected issues of HTS applications in the RF field. The reader is invited to research in some of the literature below, which itself refers to further material.

1. "High Temperature Superconductors and Their Applications in Passive Antenna Systems", Jeffrey T. Williams and Stuart A. Long. IEEE Antennas and Propagation, August 1990.

2. "Engineer's Guide to High Temperature Superconductivity", James D. Doss. Wiley-Interscience, 1989.

3. "Fabrication and Evaluation of Superconducting Devices", Babbit, Lenzing and Rachlin (US Army LABCOM). Microwave Journal, April 1991.

4. "Towards Explaining Superconductivity", John Maddox. Nature, Vol. 344, April 5, 1990.

5. "Superconductivity, a Future of Technological Excellence", Internal Report by the Du Pont Superconductivity Experimental Station, Wilmington, DE.

6. "High Temperature Superconducting Small Antennal, Technology Briefing", Foster Miller, Inc., Waltham, MA.

7. "The High Temperature Superconductivity Space Experiment", Dennis C. Webb and M. Nisenoff. (Naval Research Lab). Microwave Journal, September 1991.

8. "High Temperature Superconductors in High Frequency Fields. Fundamentals and Applications", Piel, Chaloupka and Muller, University of Wuppertal, D-56, Germany.

9. "A Survey of Possible Passive Antenna Applications of HTS", Robert Dinger, Don Bowling and Anna Martin. IEEE Transactions on Microwaves. Vol. 39, No. 9. September 1991.

10. "Measurements of Power Dependence Effects in High Temperature Superconductor Materials at Radio Frequencies", NRL Report. April 1991.

11. "A Half Loop 5000 MHz Antenna Made From HTS YBCO and TBCCO", Don Bowling and Anna Martin; Robert Dinger. 1991 DARPA HTS Workshop, 30 Sept 1991, Seattle, Washington.

12. "Superconductive Antennas", R.C. Hansen. IEEE Transactions on Aerospace and Electronics Systems. Vol. 26, No. 2. March 1990.

13. "The Effective Microwave Surface Impedance of High Tc thin Films", Klein, Chaloupka, Muller, Orbach and Piel. Bergische Universitat Wuppertal, West Germany.

14. "Superconductors and MMICs in Microwave Systems, a Special Report", Kumar Aggarwal. Applied Microwaves, Spring 1992.

15. "Passive Microwave Device Applications of High Tc Superconducting Thin Films", W. G. Lyons and R. S. Withers (MIT) Microwave Journal. November 1990.

TABLE 1 Approximate combinations of current density (J) and magnetic field (H) required for typical applications of superconductors.

Application	H (T)	J (A/cm^2)
Interconnects	0.1	5×10^6
AC Transmission Lines	0.2	10^5–10^6
Power Transformers	0.3^a–3^b	10^5
DC Transmission lines	0.2	2×10^4
SQUIDs	0.1	2×10^2
SQMEs (Energy Storage)	2.5^a–5^b	5×10^5
Motors, Generators	2.5^a–5^{b*}	4×10^4–10^{5b*}
Magnetic Separation	2–5	3×10^4
MAGLEV	5–6	4×10^4
Fusion	10–15	10^5
Fault Current Limiters	> 5	$> 10^5$

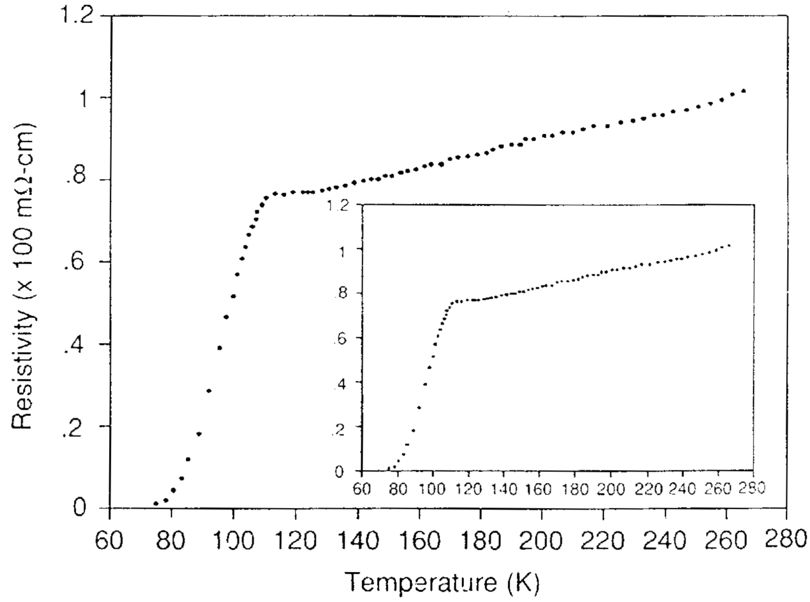


FIGURE 1. Surface resistivity vs. temperature for YBCO cooled by liquid nitrogen and (insert) by liquid helium. Univ of Alabama, Huntsville.

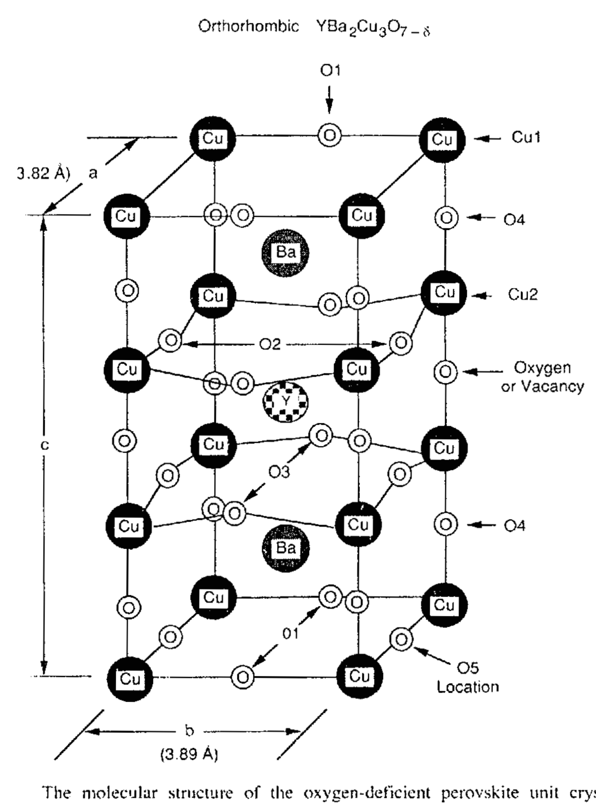


FIGURE 2. Crystal lattice structure of YBCO. James D. Doss, Ref. # 2.

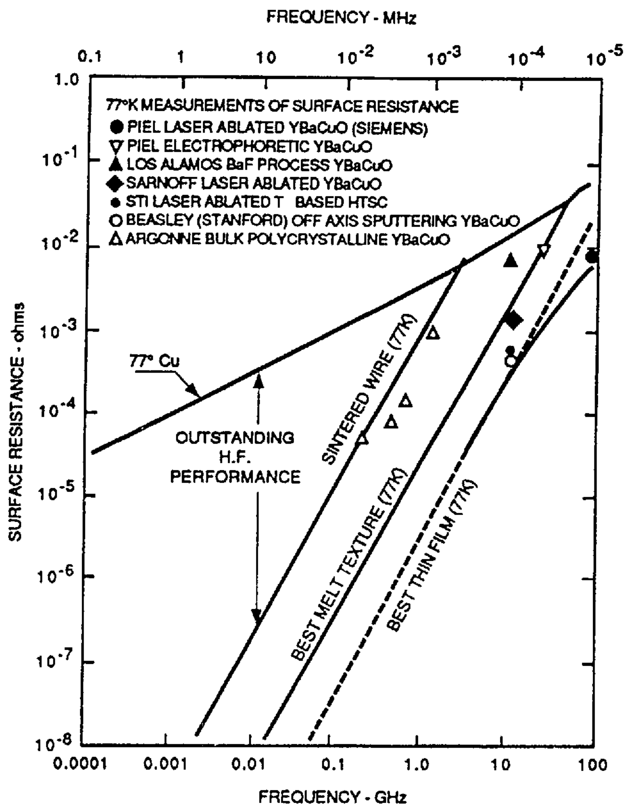


FIGURE 3

Surface Resistance of State-of-the-Art HTSC Outstanding Performance in the HF Region

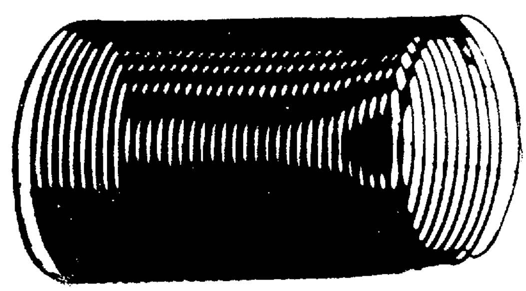


FIGURE 5. YBCO bulk coil made by extruding (sintering) and baking. This inductor and delay line is depicted in Fig. 8.

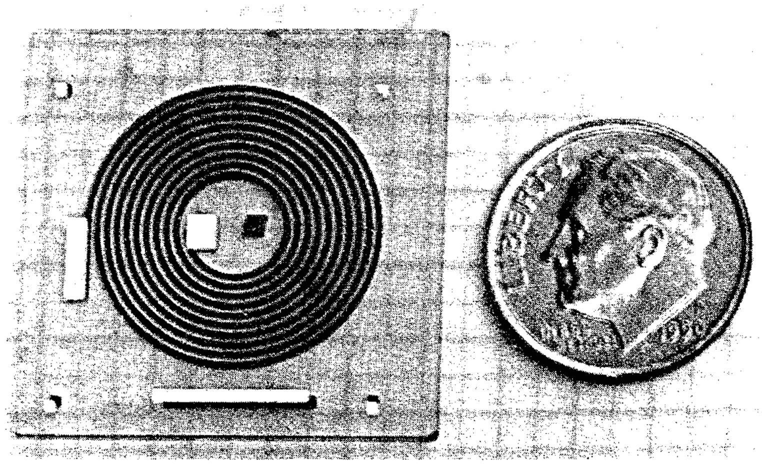


FIGURE 6. YBCO deposited and etched on sapphire to form an inductor for a microwave antenna coupler. Note silver electrodes. TRW Corp.

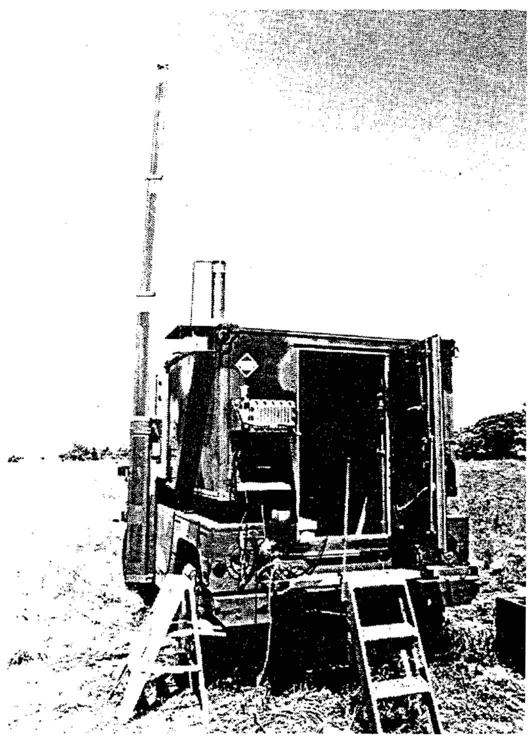


FIGURE 7. HTS-coupled top-loaded folded dipole HF antenna on a A/N TLQ-17A jammer. At left is an orthodox antenna mast. T. Tuma. CECOM IEWD

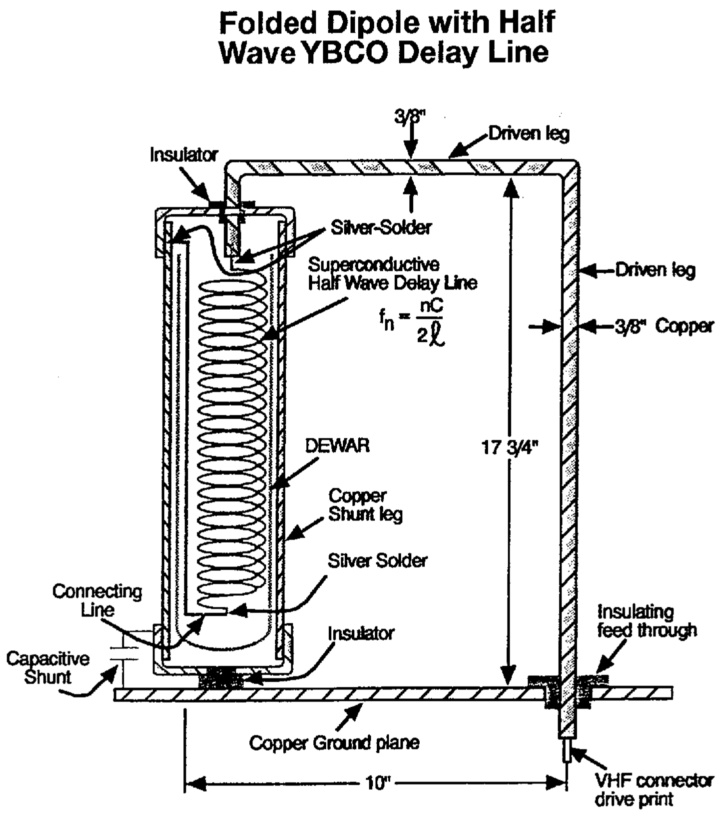


FIGURE 8. Cross section of antenna in Fig. 7. Design of Dr. Bing Chiang. Sketch by T. Tuma.

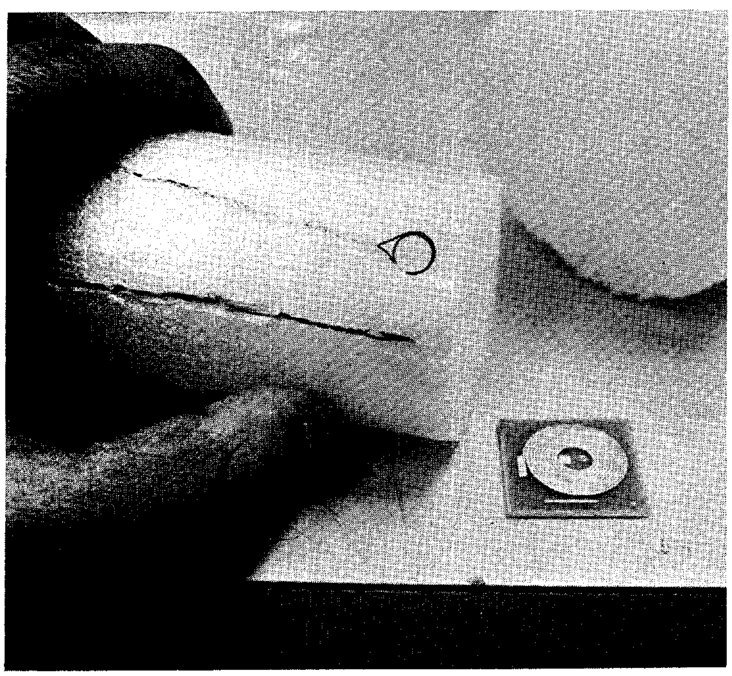


FIGURE 9. Configuration to test resonance Q of superconductive spiral inductor at TRW. T. Tuma

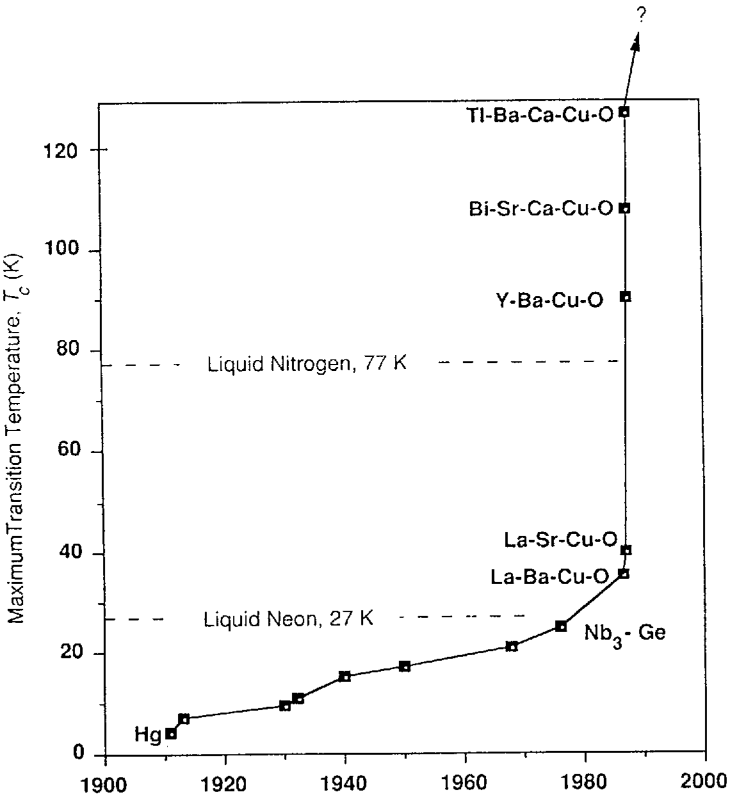
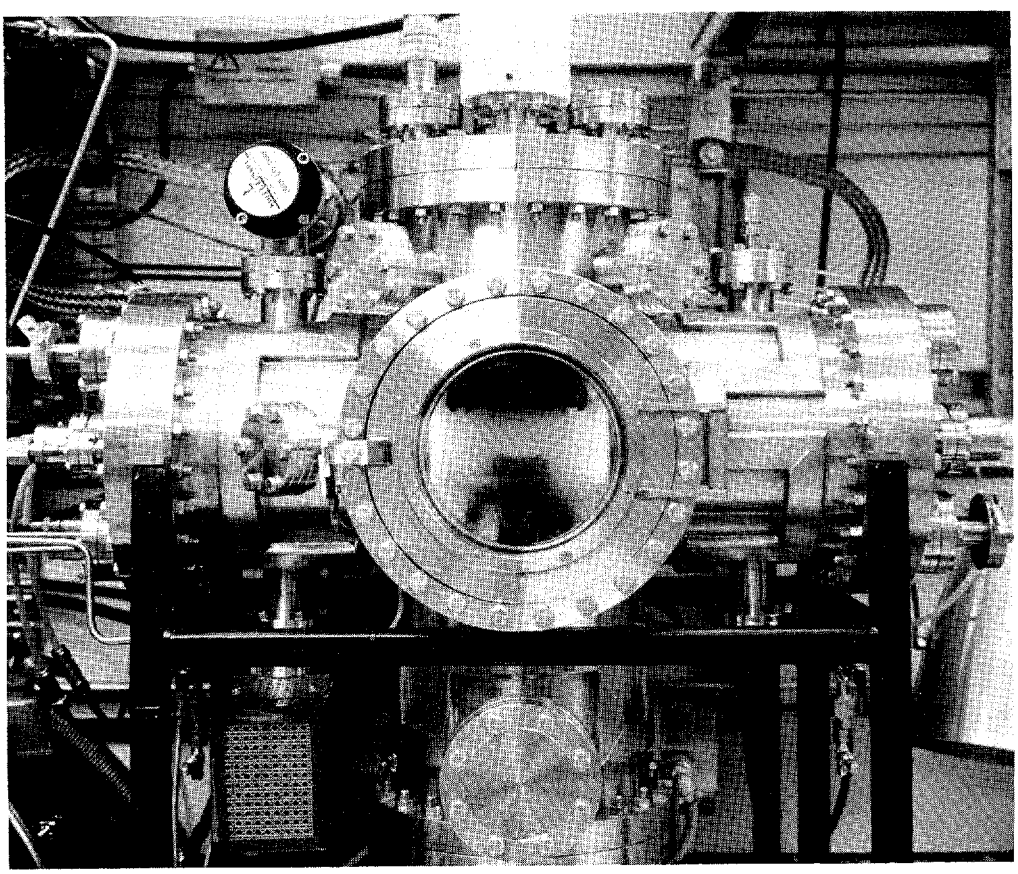


FIGURE 10. Progress made by HTSC materials.



In-situ thallium HTS thin film deposition (showing plasma discharge in a thallium atmosphere)

FIGURE 11.

Superconductivity Experimental Station
E304/C116
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MOBILE EW TRIALS FACILITIES AT DRA FARNBOROUGH

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SUMMARY

CERES and MEDUSA are two mobile laboratories housed in transportable containers, each with its own 240VAC, 50Hz generator trailer, for receiving and transmitting RF signals between 0.5 and 18GHz.

CERES is used as an RF ground truth measurement laboratory while MEDUSA can be used to radiate radar-like signals of moderate power in support of ground and flight trials of EW equipments. Each laboratory can be used in isolation while together they create a "go anywhere" EW field trials simulation and measurement facility, and they have taken part in a number of trials at various locations both in the UK and overseas.

These two laboratories are currently being enhanced by the addition of a number of small mobile signal generators which will increase the complexity of the radar signals that can be simulated and will also provide a spatially distributed array of sources. These signal generators will make extensive use of small personal computers in order to minimise costs while maintaining flexibility of operation and ease of programming. A high integrity data link will enable the signal generators to be controlled from a central processor located in CERES or MEDUSA and will also improve communication between these two laboratories. Initial results have been encouraging and a prototype system is now being produced.

MOBILE EW TRIALS FACILITIES AT DRA FARNBOROUGH

This paper describes the mobile Electronic Warfare trails simulation and measurement facilities currently operated and being developed by the Defence Research Agency (DRA) at Farnborough on behalf of the Royal Air Force Operational Requirements Branch of the United Kingdom's Ministry of Defence.

CERES and MEDUSA are two containerised mobile laboratories for receiving (CERES) and transmitting (MEDUSA) RF signals between 0.5 and 18GHz.

Each container has its own hydraulic system, powered by internal batteries. This enables the receiving and transmitting antennae to be raised and lowered and provides stabilisation and levelling at uneven sites. It also enables the CERES container to be on and off loaded from its transporter. Each laboratory requires a 15KVA, 240VAC, 50Hz supply for which it has its own generator for sites where such power is not available.

In addition we have a number of transportable RF signal sources which we are developing to produce an integrated signal generation and reception facility.

THE PASSIVE RECEIVING, DATA PROCESSING AND STORAGE SYSTEM - CERES

CERES (the goddess of harvests) is a self contained transportable laboratory for the detection and measurement of electro-magnetic radiation between 0.5 to 18Ghz, with possible future extensions to 40GHz. Its primary application is the detection and accurate measurement of radar signal characteristics in real environments and so to act as a ground truth laboratory in support of research exercises and equipment evaluations. However its usage may be extended to a wide range of electro-magnetic radiations and equipment types.

CERES accurately measures all the primary radar characteristics including Radio Frequency, Pulse Repetition Interval, Pulse Width, Polarisation, Scan Patterns, signal stability, and any interfering signals. It also has a coarse Direction-of-arrival system. It can operate in dense environments, where it can isolate individual signals for detailed analysis or provide a more general picture of the complete environment. Computer systems control the various RF receivers, the RF component selection and the data processing and display.

Primary system components are:

a. 2 major and several minor antenna systems,(dishes, horns, omni's, etc);
b. an optical tracking system with computer feedback which can control the RF antenna stacks on both CERES and MEDUSA;
c. RF amplification, filtering and distribution networks;
d. two Instantaneous Frequency Measuring receivers, a spectrum analyser, a crystal video receiver and a high speed digital oscilloscope;
e. a 2000 pulse capture and analysis unit;
f. TV cameras, video overlays, monitors and video recorder systems;

all controlled by a dedicated computer system.

Specialised analogue and digital hardware for data capture and processing has also been developed. Various DC power supplies, a 400Hz static inverter, UHF/VHF comms, intercoms and audio systems exist and a modern receiving and direction of arrival measuring system is currently being installed.

The CERES laboratory (in its original bus) acted as a ground truth monitor during the NATO "MACE V" trials investigating the effectiveness of combined chaff and jamming against modern radar systems at Captieux Range, Mont-de-Marsan, France. Since then it has been rebuilt and has taken part in a number of ground and flight trials at various locations in the UK.

Presented at an AGARD Meeting on 'Challenge of Future EW System Design', October, 1993.

THE ACTIVE MULTIPLE TRANSMISSION AND RADAR SIMULATION SYSTEM - MEDUSA

MEDUSA (the lady whose looks could kill) is a self contained mobile laboratory for the transmission of medium to high power RF signals between 0.5 to 18GHz, with possible future extensions to 40GHz. Its primary application is to generate test and simulated radar signals in free space in support of evaluation exercises of research and project equipments both for ground trials and flight trials at DRA, MOD or RAF/RN major ranges. Investigation into propagation effects in conjunction with CERES is also possible.

With its RF simulation, distribution, and transmission hardware, (some specially developed), and its limited on board monitoring facilities (normally performance checked by CERES), MEDUSA can simulate a wide range of RF signal types at ERPs capable of exercising the full dynamic range of receivers at short test ranges, and enabling signal detection at ranges beyond 10 Km on flight trials. All the primary radar characteristics (RF, PRF, Pulse Width, Scan and Burst periods) can be accurately simulated, plus engagement sequences and multiple signals. Linear polarisation changes are also possible.

The primary system components of MEDUSA are:

a. 3 dish antennae and turntables, (plus optical tracker);
b. multiple hardware (PROM) programmable pulse generators;
c. multiple RF sources, modulators and amplifiers (up to 4KW);
d. signal monitoring equipment including power meters, spectrum analyser, and oscilloscopes;
e. a Cossor IFF interrogator to aid antenna steering at long ranges;
f. TV camera and monitor system to aid antenna steering at short ranges;

plus various power supplies, and 400Hz static inverters.

Recent activities involving MEDUSA have been:
Simulating an RF jammer during the evaluation of a digital RF memory system being developed in the UK;
Producing potentially interfering RF signals during the evaluation of a prototype ESM equipment both at DRA Farnborough and close to radar transmitters at other locations, and;
Acting as an RF beacon to calibrate airborne equipment during flight trials at DRA Farnborough.

THE COFFINS

CERES and MEDUSA are currently enhanced by a small number of simple RF transmitters known as COFFINs.

Each COFFIN contains a pre-programmable hardware radar simulator, which can generate repeated Pulse Interval, Pulse Width and Antenna Scan sequences, linked to an RF signal generator with a pulse modulation capability, and a digitally controlled RF attenuator. These and the necessary power supplies are housed in a weatherproof man-portable container on which is mounted a fixed antenna. The COFFINs enable pre-set radar-like signals to be generated from points remote from CERES or MEDUSA.

THE FURIES - SINGLE RADAR SIMULATOR UNITS.

The FURIES (sent by the Gods to torment men) will be a low cost enhancement to the two mobile laboratories. They will provide a capability to generate spatially separated radar-like signals from an array of small transmitters placed around CERES or MEDUSA. The FURIES will supplement the current hardware preprogrammed simulators (COFFINS), but will simulate more complex radar systems and engagement sequences. The heart of the FURIES system will be a number of Remote Signal Generators (RSGs) controlled from a Master Processor residing in CERES or MEDUSA and communicating with the RSGs via a two-way optical fibre link which will maintain its integrity with a single break.

Each Remote Signal Generator will be housed in a weatherproof man-portable container and consist of a small Personal Computer containing:

a. a high speed single board processor;
b. special pulse interval and pulse width countdown circuits controlled by a crystal clock with a minimum 5MHz frequency;
c. At least 512K bytes of memory for Pulse Amplitude, Interval, Width and RF data storage;
d. At least 1M bytes of memory on removable hard disc;
e. A 3.5" floppy disc drive;
f. All necessary output ports to the RF modulating elements; and
g. A control input/output port linking this Personal Computer to a central Master Processor via optical cables and suitable interfaces.

Other elements of the FURIES will be:

a. One or more RF signal generators capable of pulse modulation and RF control via a standard equipment interface such as HPIB or IEE488;
b. One or more digitally controlled RF attenuators;
c. RF signal combiners, feeds, and a fixed or steerable antenna; and
d. All necessary interface units, power supplies, etc.

The functions of the Personal Computer will be:

a. To accept data from pre-prepared files on 3.5" floppy discs and load these data into the appropriate memory locations;
b. To accept data and commands from its own keyboard or from a Master Processor via a fixed format I/O control link such as RS232; and
c. To run programmes to read and replay the data in a predetermined manner to specified outputs, both independently and under the interactive control of a Master Processor.

The basic data will consist of an array of amplitude versus time values for Antenna Scan data, arrays of time intervals for Pulse Interval and Pulse Width data, and an array of RF words for some degree of pulse by pulse RF agility.

The simulation will allow Pulse Interval, Pulse Width, RF and Antenna Scan sequences of up to 32K points with an amplitude range of at least 64 dB to be generated and repeated infinitely. Off-line software will allow several scan patterns to be merged together to produce a complex amplitude sequence and to combine this with selected pulse data sequences.

The FURIES began with a prototype system using two Lap-Top Computers. One Computer acted as the Master Controller while the other was linked to an RF signal generator and a digitally controlled attenuator and acted as a stand-alone Remote Signal Generator or as a Remote Slave. The stand-alone unit has been field tested with encouraging results and a larger system of a Master

Processor, two Remote Slaves and Fibre Optic interconnections, has now been developed.

FUTURE PLANS
Future plans are aimed at improving the integration of the CERES, MEDUSA and the FURIES while still allowing each to operate independently if required. Once the prototype FURIES system has been validated we shall extend it to at least six RSGs with RF sources, antennas and some form of housing. This will include an enhanced RSG to replace the current hardware pulse generators in MEDUSA and so include MEDUSA within the FURIES system. Without the need for portability the RSGs in MEDUSA can be as complex as required. The FURIES Master could be mounted in CERES, making it possible to remotely control and monitor the emissions from MEDUSA and the dispersed RSGs, or in MEDUSA, or at any convenient location.

A stand-alone FURIES system could have many uses. An aircraft system check from a FURIES source before take-off could avoid many aborted sorties. Furthermore, if the FURIES were grouped into an array they could be programmed to simulate a source moving across the array. One could then use the FURIES to measure the DF performance of an EW equipment both statically and dynamically, although a realistic dynamic representation would require careful antenna positioning and software control.

In conclusion CERES, MEDUSA and the FURIES provide a flexible and comprehensive system which is available as a "go anywhere" EW field trials simulation and measurement facility and which has proven its worth in trials both in the UK and overseas.

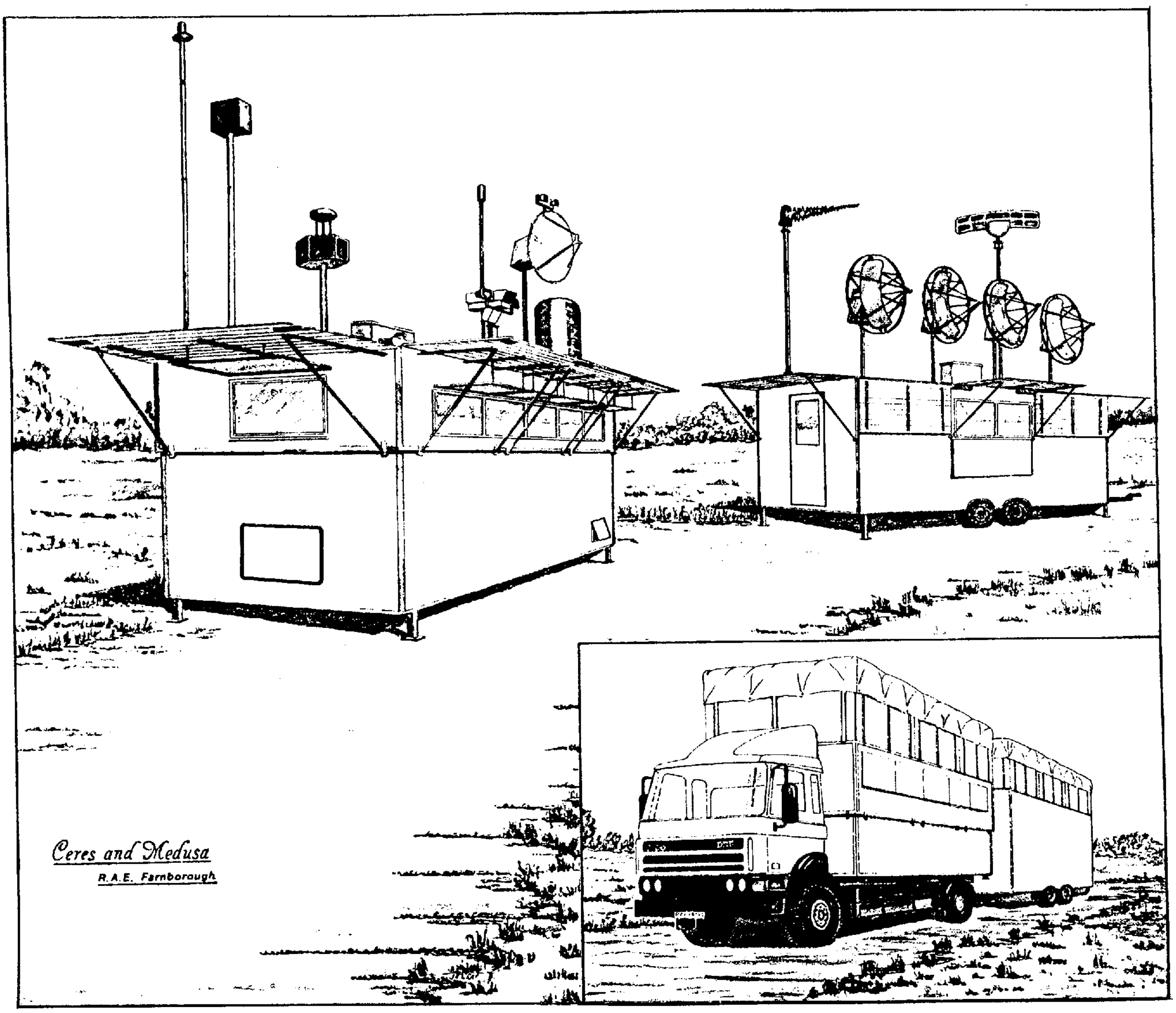

Figure 1

MOBILE EW TRIALS FACILITIES
AT THE
DEFENCE RESEARCH AGENCY
FARNBOROUGH

CERES	**a mobile signal capture and analysis laboratory**
MEDUSA	**a mobile signal generation laboratory**
The COFFINS	**transportable pre-programmed signal sources**
The FURIES	**an integrated distributed signal generation system**

Figure 2

CERES

(THE GODDESS OF HARVESTS AND INGATHERING)

USES COMPUTER CONTROLLED
- **OMNIDIRECTIONAL, DISH AND HORN ANTENNAE,**
- **RF AMPLIFIERS AND FILTERS,**
- **INSTANTANEOUS FREQUENCY MEASURING RECEIVERS,**
- **SPECTRUM ANALYSERS,**
- **HIGH SPEED DIGITAL OSCILLOSCOPES,**
- **2000 PULSE CAPTURE, ANALYSIS AND DISPLAY SYSTEM,**

TO MEASURE AND RECORD THE
- **RADIO FREQUENCY,**
- **PULSE INTERVAL,**
- **PULSE DURATION**
- **PULSE AMPLITUDE,**
- **SCAN PATTERN,**

OF RADAR-LIKE SIGNALS BETWEEN 0.5 AND 18 GHz

AND PROVIDE A GROUND TRUTH MEASUREMENT DURING EW TRIALS

Figure 3

MEDUSA

(THE LADY WHOSE LOOKS COULD KILL)

USES
HARDWARE (PROM) PROGRAMMABLE PULSE GENERATORS
RF SOURCES, MODULTORS AND AMPLIFIERS (UP TO 4KW),
LOCAL SIGNAL MONITORING EQUIPMENT,
STEERABLE DISH ANTENNAE CONTROLLED BY
A TV CAMERA FOR SHORT RANGE TARGETS
AN IFF TRACKER FOR LONG RANGE TARGETS

TO SIMULATE RADAR-LIKE SIGNALS BETWEEN 0.5 AND 18 GHz

AND SO GENERATE SPECIFIC SIGNALS DURING EW TRIALS

Figure 4

THE COFFINS

(TRANSPORTABLE SINGLE RADAR SIMULATORS)

EACH COFFIN IS A WHEELED WEATHERPROOF BOX CONTAINING
A PRESET (PROM) PROGRAMMABLE PULSE GENERATOR
AN RF SOURCE, MODULTOR AND AMPLIFIER (UP TO 10W),
A FEED TO A FIXED HORN ANTENNA MOUNTED EXTERNALLY

TO SIMULATE RADAR-LIKE SIGNALS BETWEEN 0.5 AND 18 GHz

AND GENERATE SPACIALLY DISTRIBUTED SIGNALS DURING EW TRIALS

Figure 5

THE FURIES

(SENT BY THE GODS TO TORMENT MEN)

EACH FURY WILL BE A WHEELED WEATHERPROOF BOX CONTAINING
A FULLY PROGRAMMABLE REMOTE SIGNAL GENERATOR
RF SOURCES, MODULTORS AND AMPLIFIERS (UP TO 10W),
A FEED TO AN EXTERNAL ANTENNA
AN EXTERNAL FIXED OR STEERABLE ANTENNA

LINKED BY OPTICAL FIBRES TO A CENTRAL CONTROL COMPUTER

TO GENERATE SPACIALLY DISTRIBUTED COMPLEX RADAR-LIKE SIGNALS BETWEEN 0.5 & 18 GHz

WHEN FULLY DEVELOPED THIS SYSTEM WILL LINK CERES, MEDUSA AND THE FURIES INTO AN INTEGRATED MOBILE EW TRANSMISSION AND RECEPTION SYSTEM

Figure 6

FUTURE PLANS

Integrate CERES MEDUSA and the FURIES, but . . .
Allow each to operate independently when required.

Build a FURIES system with six Remote Units.

Develop an enhanced Remote Unit for MEDUSA

Include MEDUSA within the FURIES system.

Put FURIES Master in CERES or MEDUSA or any convenient location.

Use a FURIES unit to check aircraft system before take-off.

Use a FURIES array to check DF system performance
both statically and dynamically.

Figure 7

ECM Stimulation Techniques Using Digital RF Memories

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SUMMARY

The provision of programmable ECM techniques using digital RF memories (DRFM) as the receiver/source is described. By using the DRFM to coherently re-generate radar signals, most radar types including Pulse Doppler can be subjected to the effects of numerous ECM techniques. The applications of the ECM stimulator are highlighted together with typical ECM responses generated by the equipment.

List of Symbols/Abbreviations

A/D	Analogue-to-Digital
D/A	Digital-to-Analogue
DDS	Direct Digital Synthesiser
DFD	Digital Frequency Discriminator
DRFM	Digital Radio Frequency Memory
ECCM	Electronic Counter-Countermeasures
ECM	Electronic Countermeasures
ESM	Electronic Support Measures
EW	Electronic Warfare
GHz	Giga Hertz (10^9Hz)
Hz	Hertz
LO	Local Oscillator
MHz	Mega Hertz (10^6Hz)
msec	Milliseconds (10^{-3} seconds)
PC	Personal Computer
RF	Radio Frequency
RGPO	Range Gate Pull Off
sec	Second
TWS	Track-While-Scan
µsec	Micro-seconds (10^{-6} seconds)
VDU	Visual Display Unit
VGPO	Velocity Gate Pull Off
W/Hz	Watts per Hertz

1. INTRODUCTION

The advent of digital RF memories (DRFM) has significantly enhanced many electronic warfare (EW) countermeasure systems and particularly airborne jamming equipment. There are now several jamming pods in service with DRFMs and many either under development or in the final stages of production.

The proliferation of DRFMs has occurred because of their unique signal capturing and replication capabilities which allow the reception and retransmission of coherent (crystal-controlled) radars with a high degree of fidelity. This new technology within the EW community also presents a new and powerful test and training capability when integrated into EW stimulation equipments.

Stimulation (as opposed to simulation) identifies a real-time signal generator controlled by software with simulation defining a software (usually non real-time) model running on a computer.

With defence budgets continually under severe reduction measures, the effectiveness of EW and radar systems can be increased by comprehensive training and testing using low-cost realistic stimulators. This paper presents a new type of ECM stimulator, code named CHAMELEON, ideally suited for training and testing of both EW and radar operators.

2. DRFM TECHNOLOGY

A DRFM is essentially a microwave receiver which samples received radar signals at a high rate and stores the signals in a memory. These stored signals can then be recalled when required to re-transmit the received sampled radar signals. The properties of this basically simple device provide an inherent built-in ECM facility to the user - radar deception both in time and in frequency.

The basic block diagram of a DRFM is illustrated in Figure 1. This figure illustrates a phase sampled device architecture although amplitude sampling is also possible to produce a similar effect.

Wideband (or narrow band if required) RF signals are amplified by an RF limiting amplifier prior to mixing (down-converting) with a fast-tuned local oscillator (LO). The resulting output is at baseboard with a typical bandwidth of ±250MHz. A fast A/D converter is used to produce digitised signals representing the in-phase (I) and quadrature (Q) RF signals and these signals are stored into fast memory by first carrying out a serial-to-parallel conversion, followed by a parallel WRITE into memory.

To recall a stored signal, the memory is addressed and the reverse operation carried out. In Figure 1, a further mixing process is used in association with a direct digital synthesiser (DDS) to produce Doppler shifts (i.e. moving target effects). Thus the DRFM provides a powerful receive/transmit facility under control of an externally provided process. An example of the DRFM

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operation is illustrated in Figure 2 in which a chirped pulse is stored and regenerated. The figure clearly illustrates the fine-grain replication process.

The key to the effectiveness of the DRFM sub-system is the control of the device and in CHAMELEON, this is carried out by a set of digital control printed circuit boards (Techniques Generator) which are driven by the user using a PC with interactive software.

3. ECM STIMULATOR

The CHAMELEON architecture is illustrated in Figure 3. In particular it should be noted that CHAMELEON provides both a moving target signal (skin echo) with an ECM technique superimposed to give maximum applicability for testing. Referring to the figure it can be seen that the heart of the ECM stimulator is the DRFM and when coupled together with the signal processing and control facilities of the associated hardware, a fully programmable jammer is realised. The programmability of CHAMELEON is one of its key features which enables a wide range of ECM techniques to be generated. The following major techniques are discussed: Range gate pull-off (RGPO), velocity gate pull-off (VGPO), scan deception and wide-band noise generation.

3.1 RGPO Implementation

RGPO is an ECM deception technique which attempts to deceive a tracking radar by breaking its lock on a target. This is simply realised in CHAMELEON by carrying out a programmed delay of the re-transmitted pulse over a period of time. The delay can either be linear (velocity) or parabolic (acceleration) depending upon the user's requirements. The DRFM is able to store and re-transmit radar signals up to 204µsec in length and this range covers the majority of signals applicable to the RGPO technique.

Typical RGPO parameters are illustrated in Figure 4. It can be seen that the user has a very wide range of parameter values for RGPO (and for all techniques) and this enables application of the stimulator to a large number of radar system types. A feature of this RGPO implementation is also a straight-through repeater mode in which the memory is by-passed.

As RGPO is basically a programmed READ of the DRFM, similar control techniques can be carried out to generate false targets. This is also provided by the system software and hardware.

3.2 VGPO Implementation

Velocity deception requires a considerable coherency in a jammer and the DRFM is ideal in this case. As seen in Figure 1, the DRFM architecture includes a DDS sub-unit under the control of the techniques generator. This DDS is a fast switching, high resolution (3Hz) device which provides Doppler shifts, both + and –, to the retransmitted signal. This allows both VGPO and moving target simulation to be either toward the radar or away from it.

VGPO programmability is similar to RGPO in terms of range of parameters and deception equations (linear or parabolic). Once again, the user has complete control of all parameters in the technique thereby enabling considerable flexibility for training and testing purposes. In particular, with a resolution of 3Hz and a maximum Doppler shift of 125KHz, most scenarios can be easily accommodated. An example of a fixed frequency VGPO output (15.6KHz) is illustrated in Figure 5. This particularly illustrates the high original carrier suppression of 70dB.

VGPO and RGPO can be combined simultaneously in CHAMELEON to provide coherent range and velocity deception. Without the DRFM, this combined technique would be difficult to implement.

3.3 Scan Deception

CHAMELEON offers two basic programmable forms of scan deception - audio or swept audio modulation, (particularly for conical scanning radars), and inverse gain deception. Audio modulations up to 10KHz are programmable either at a fixed frequency or swept over a specified range at a specified sweep rate. Typical values are 10Hz to 10KHz modulation ranges with 0.1sec to 25sec sweep rates. The technique is used to deceive conical scanning radars by transmitting the conical frequency back to the radar but out of phase and amplitude.

Inverse gain deception is provided with an amplitude measuring receiver (RF LOG video), interactive system software and a hardware look-up table. The operator selects a signal to be jammed and its scan pattern is measured and displayed on the PC VDU. The user then selects an amplitude range over which inverse gain is to operate (typically 40dB) and the PC in association with the Techniques Generator calculates a table of inverse amplitude values.

When initiated, inverse gain is carried out on a pulse-by-pulse basis for an operator specified length of time. A representation of the technique is illustrated in Figure 6. This ECM technique is widely used for angle deception against several classes of radars including search, conical scan and TWS radars.

3.4 Noise Jamming

The provision of the DDS sub-section in association with DRFM enables wide band (or narrow) noise to be generated either coherently against a received radar or non-coherently in a stand-alone mode. The noise is generated by randomly changing the DDS frequency very rapidly using a pseudo-random addressing sequence. This method produces a flat programmable spectrum, as illustrated in Figure 7. The bandwidth control is especially notable as well as the uniform power density (W/Hz).

CHAMELEON allows programmable bandwidths from 100KHz to 100MHz and sweep rates from 20msec to 2µsec over bandwidths up to ±50MHz around the carrier frequency. When coupled with high power travelling-wave tubes and antenna systems, virtually all classes of noise techniques can be effectively generated by the system.

4. APPLICATIONS

ECM stimulation is a new but growing technique for a variety of training and testing applications. A contract is currently underway for a NATO Air Force for a system incorporating CHAMELEON with many additional system features including the provision of simultaneous target and technique RF signals. This allows simulated airborne ECM whilst remaining in a covert ground site as illustrated in Figure 8.

Particular recent trends for such equipments are for air-defence radar operator training in a similar context to that illustrated in Figure 8. This is of particular importance following events encountered during the Gulf War. The range of techniques available and the flexibility of parameter ranges enable most ECM scenarios to be generated against air-defence radar operators.

A second new area is the testing of radar systems in terms of detailed performance against ECM techniques. This of course is relevant to the radar manufacturers and the flexibility of CHAMELEON provides a considerable range of test facilities for evaluating radar ECCM effectiveness.

Finally, many countries are now utilising the services of airborne ECM training companies which provide threat generation mainly against ground or naval installations. An example of this is NATO MEWSG and the incorporation of the flexible performance offered by CHAMELEON in an airborne pod will greatly enhance the training currently offered.

5. CONCLUSIONS

The tightening of defence budgets worldwide has put more emphasis on 'on-the-ground' training and testing. The advent of a new family of programmable ECM stimulators using DRFM technology opens up many areas of application of these equipments in both fixed and mobile situations at radar and EW sites. CHAMELEON offers a wide range of classic ECM techniques to be generated with minimal operator training but with exemplary performance.

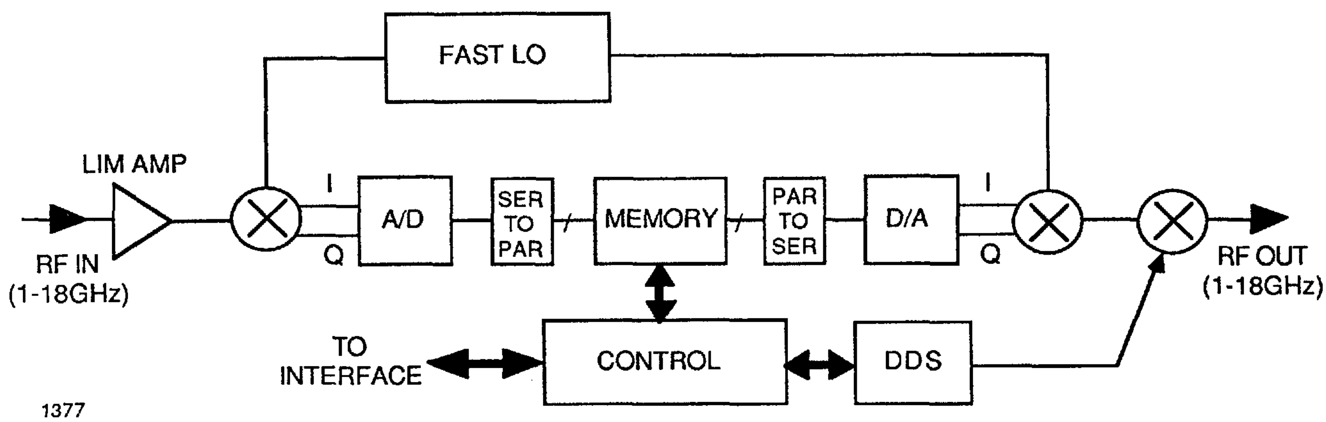
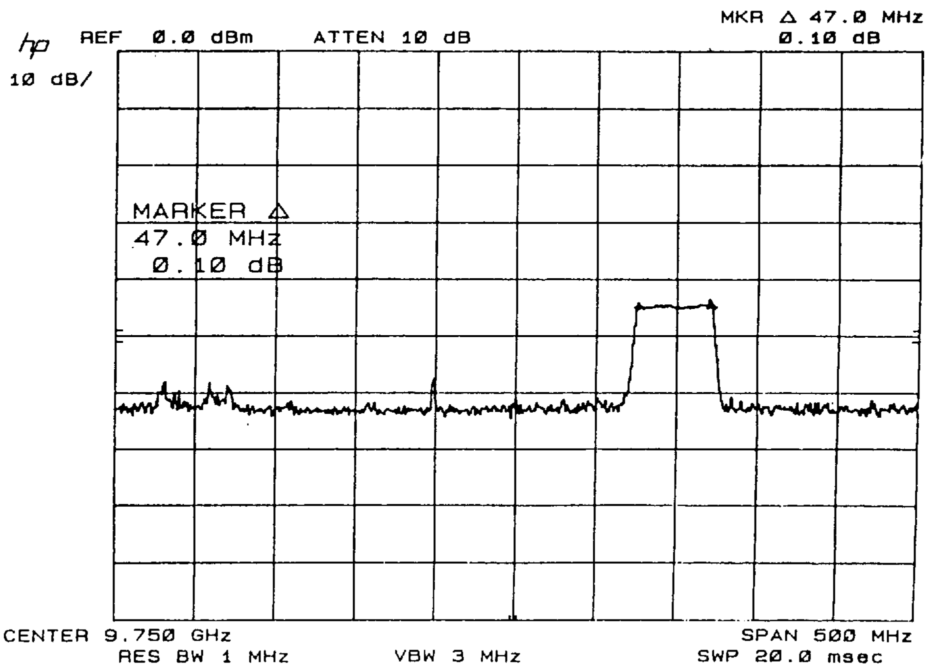
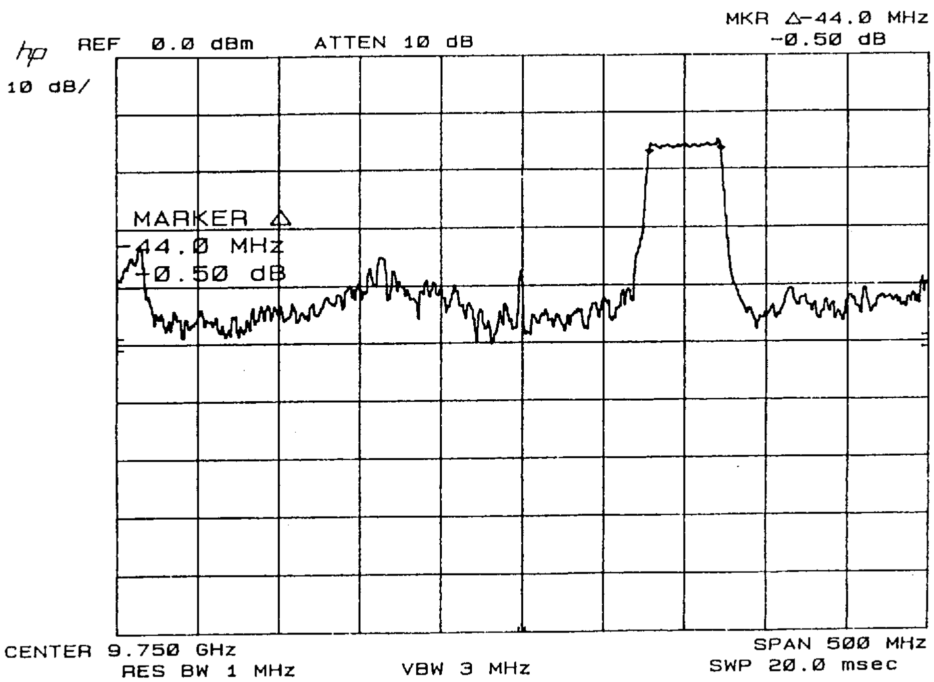


Figure 1 - Basic DRFM



45 MHz CHIRP INPUT TO DRFM
FREQUENCY DOMAIN



REPLAYED 45 MHz CHIRP
FREQUENCY DOMAIN

Figure 2 - DRFM Storage and Re-transmission of CHIRP Signal

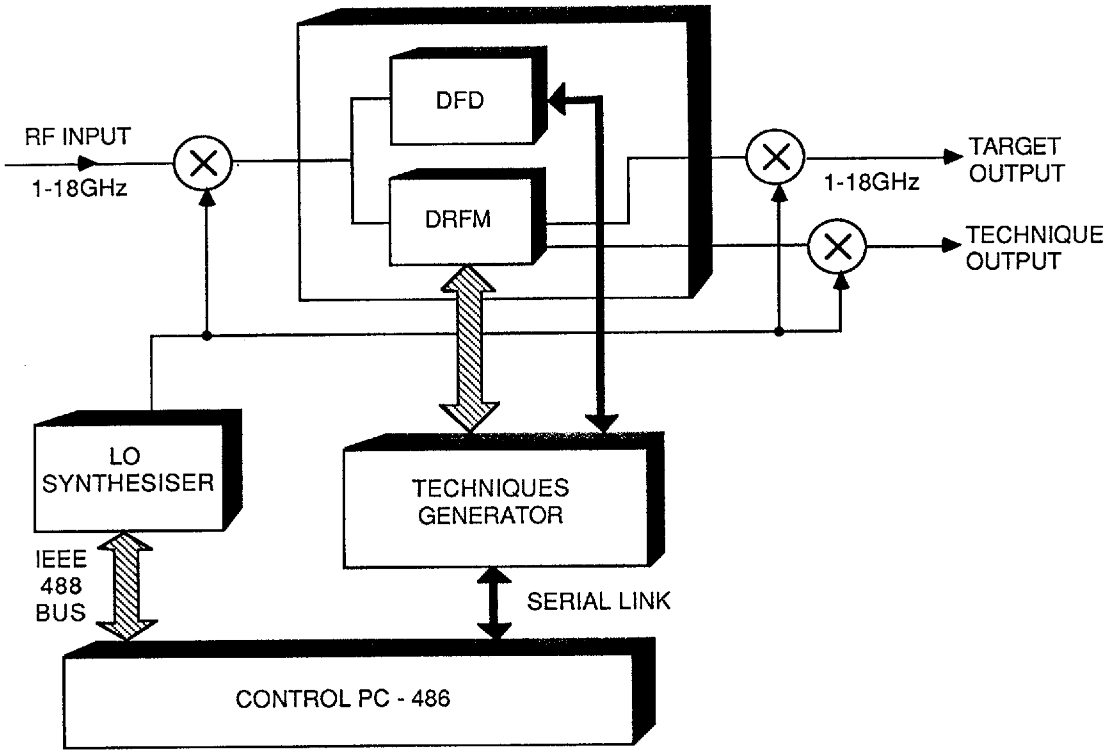
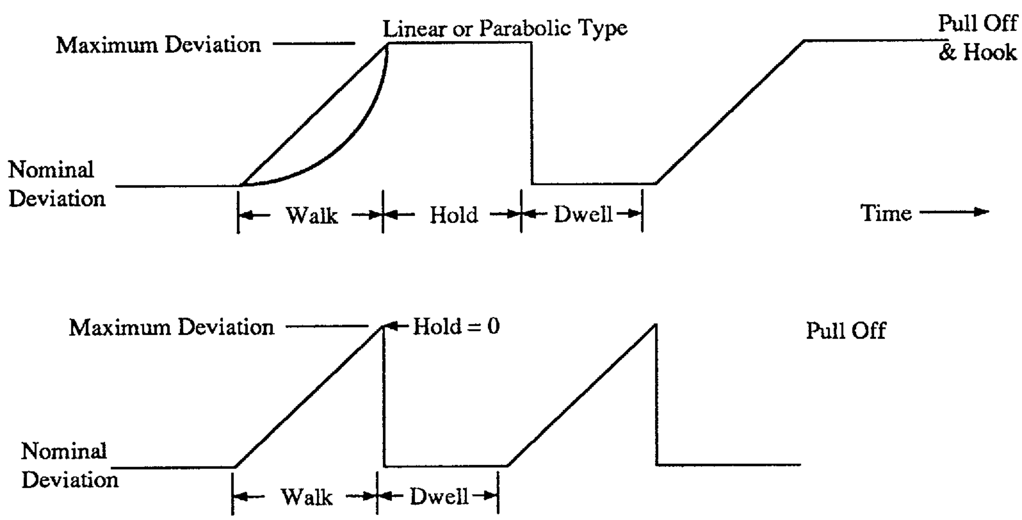


Figure 3 CHAMELEON Architecture



Walk Time	:	0 - 25 seconds
Dwell Time	:	0.05 - 12 seconds
Hold Time	:	0 - 12 seconds
Max Deviation	:	0.2 - 100 μsec
Max Velocity	:	1000 m/sec
Max Acceleration	:	75 m/sec

Figure 4 RGPO Characteristics

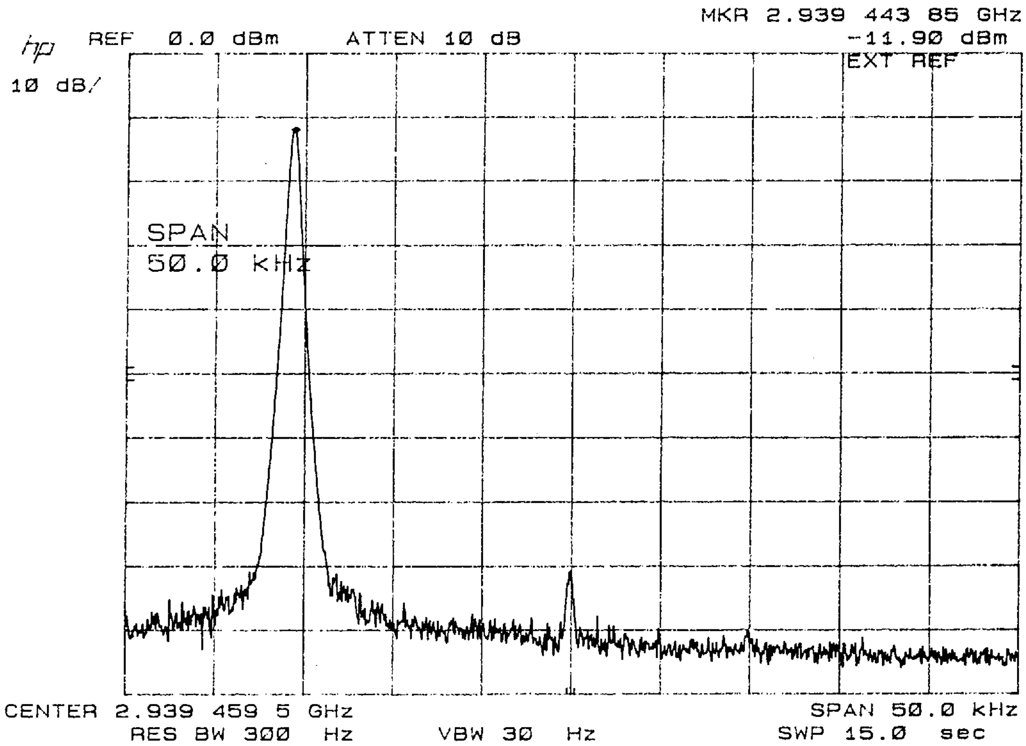


Figure 5 - VGPO Fixed Doppler Shift Example

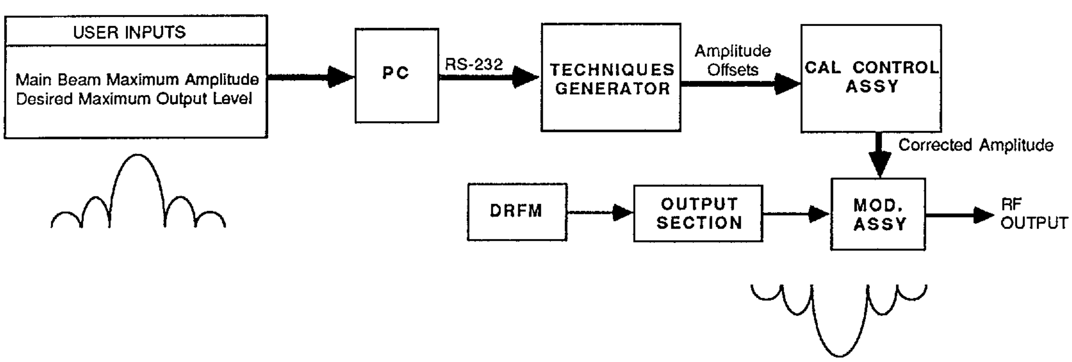


Figure 6 Inverse Gain

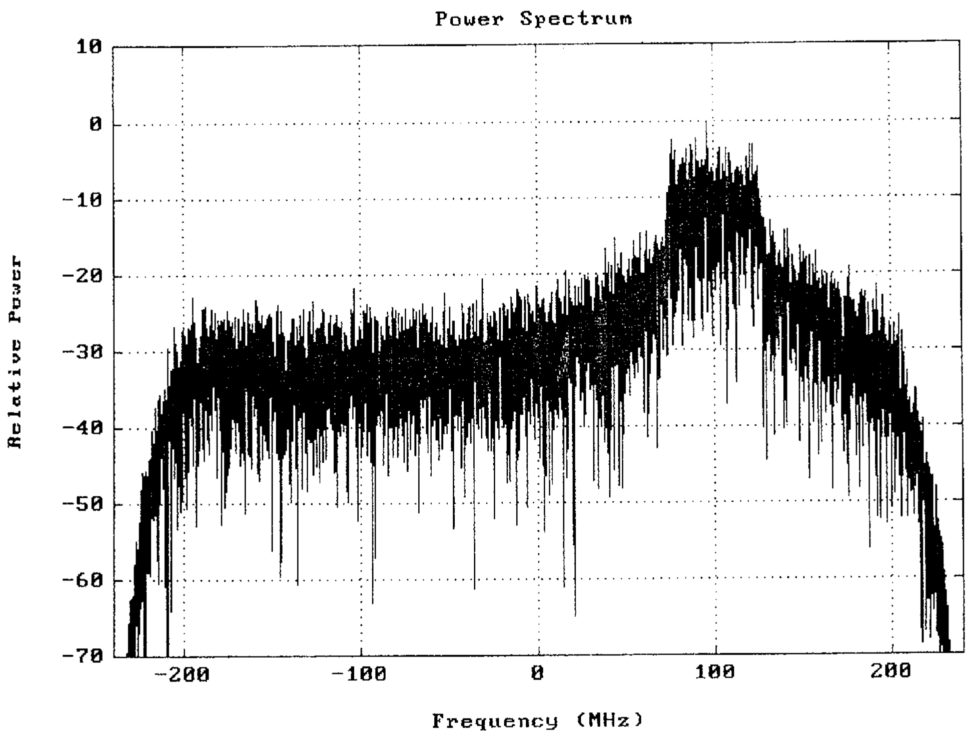


Figure 7 - 50 MHz Noise Generation

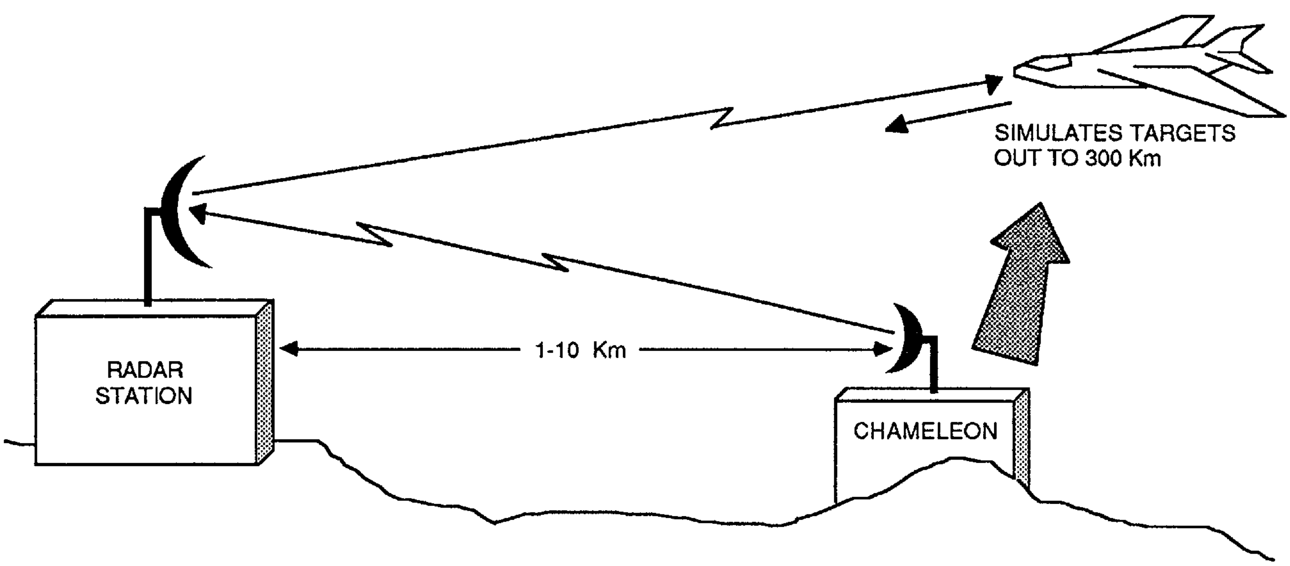


Figure 8 CHAMELEON Application

Discussion

DISCUSSOR : **M. P. CHALTIEL (FR)**

How many bits are used in the DRFM for quantization ?

Author's reply :

3 bits in each of the I and Q channels resulting in 45° phase quantization.

MESA : Modular Interactive Electronic Warfare Simulator suited to the coverage of EW Equipment life cycle

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ABSTRACT

Many defence-related investigations cannot be conducted at full scale for obvious practical reasons of cost, time, technological resources, etc.

Fortunately, rapid development of computer sciences contributed to the creation of simulation tools used for the definition, development, testing and implementation of systems, equipment or strategies. This applies in particular to Electronic Warfare, which has turned out to be a key factor to successful missions.

MESA is a family of Electronic Warfare simulators developed by DASSAULT ELECTRONIQUE for the design, development, integration and operational support of his equipment. To each activity a type (either digital or hybrid : software + hardware) and a simulation level (either global, behavioral, or detailled) assigned, whatever the environment it is conducted in (industrial or operational). This is applied in order to meet the requirements of the specifications while keeping operational requirements in mind (missions, scenarios) throughout the equipment life cycle.

1. INTRODUCTION

No doubt that the capabilities offered by advanced techniques and technologies, as well as the knowledge gained by the experience of recent conflicts definitely proved the considerable role of Electronic Warfare in the success of military missions and in the vulnerability of the equipment used during said missions.

In this field, the complex and dynamic character of the phenomena involved, as well as their interrelations with the other characteristics of the mission (flight paths, terrains, interconnected defence systems) have stressed the need for the integration of the operational requirement at the "system" level. It is thus no longer possible to design Electronic Warfare systems from purely theoretical technical considerations and to reason in terms of elementary duels only.

Luckily, the rapid development of computer technologies allowed the creation of ever more sophisticated simulation tools. Computer-based simulation created innovative working methods and enlarged the field of future investigation. It proved to be an indispensable tool used in most studies at various levels. Computer-based simulation allows more systematic approach of problems, clear definition of the role of key parameters from the beginning, and explanation and quantizing of requirements.

Eventually, simulation enhances problem awareness by bringing in concreteness, and proves to be a valuable time- and money-saving technique.

Presented at an AGARD Meeting on 'Challenge of Future EW System Design', October, 1993.

Simulations are nowadays required to develop, design or investigate any complex equipment or system. Such simulations however are not systematically implemented at the same level nor at the same development point of a system's life.

The point we want to discuss here is: how can we guarantee the consistency of simulation tools throughout the equipment life cycle to effectively meet operational requirements.

2. SIMULATIONS IN AN ELECTRONIC WARFARE SYSTEM LIFE CYCLE

2.1. General

The life of an Electronic Warfare system can generally be splitted into five main stages:

- elaboration : prospective investigations, statement of requirements,
- definition : technico-operational dimensioning and feasibility studies,
- development : design, production, integration,
- validation : performance check versus specifications,
- operational use : operation.

These five stages describe the traditional "V cycle" of equipment development, illustrated by Figure 1 below. Note that the first and last stages lie under the responsibility of military forces or their representative technical departments, whereas the three intermediate phases are the manufacturer's responsibility.

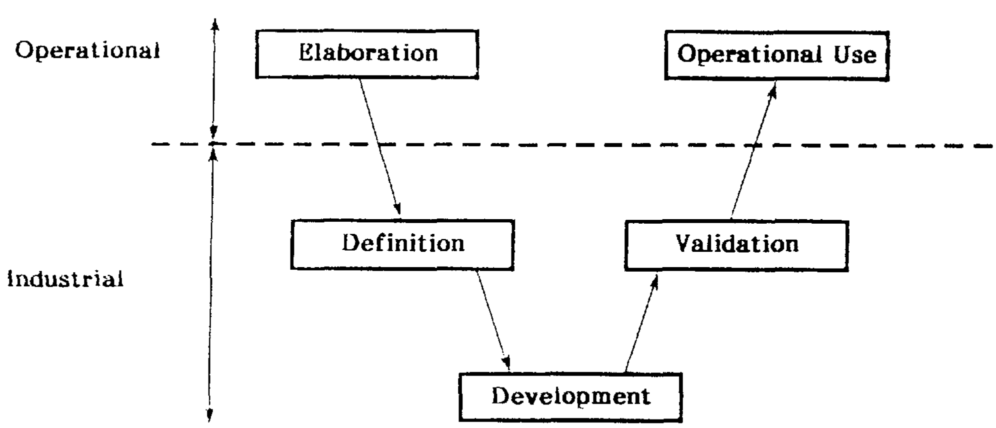
2.2. Elaboration Phase

The purpose of this technico-operational phase is to estimate the performance objectives to be set for the planned Electronic Warfare system. For this purpose, it is necessary to model the enemy resources which may be encountered, the missions to be performed and the scenarios wherein such missions are executed.

Systematic and detailed modeling of the different opponents, however, would rapidly lead to an "overinflated" computerized product, thereby hindering easy use, in particular for statistics-oriented research.

Fig. 1

V Cycle of EW System Development



It is therefore necessary to elaborate global digital models based on parametric research, in order to study and compare the respective advantages of various solutions, by resolving multitarget and multiple-weapon system problems.

2.3. Definition Phase

This phase bridges the gap between the technico-operational and technical studies relative to the Electronic Warfare system design.

At this point, where precise system's definition is not yet acquired, it is impossible to use specific models since they could be prejudicial to the dimensioning approach: actually, the point is to translate operational requirements into technical terms and to highlight the dimensioning parameters in relation with the other concurrent theoretical studies and the technique and technology-oriented feasibility studies.

The simulations required at this stage are global simulations related to operating logics (typical scale: 100 ms). They are based upon parametric models of weapon systems, Electronic Warfare systems and scenarios. The technical level of such models has to allow the representation of dimensioning phenomena without estimating the influence of 2nd-order parameters.

From a practical point of view, the simulation tools used are of the same type as those used in the preceding phase, which illustrates the necessity to integrate a single reference scenario for both phases. The operating tools used for the definition phase are however oriented towards a technical rather than operational representation.

2.4. Development Phase

The Electronic Warfare system development generally takes place within the chronological framework where hardware subassemblies are produced and validated with their own software programs, in order to be later on incorporated within a total management software system.

The development of this latter type of software can benefit from detailed digital models of subassemblies (provided this has been planned), in order to develop high-level software functions on scenarios, in particular the reference scenarios announced during the first phase.

As an example, the detection and sorting capabilities of warning receivers or ESM systems in a dense environment can be grasped on scenarios by modeling events at the pulse level or even at a more detailed level (intrapulse modulation).

Detailed models corresponding to subassemblies are obviously specific and could be obtained, for example, through the use of elementary "hybrid" simulations involving stimulations adapted to each isolated subassembly and inserted into the loop of elementary simulations. The software models of subassemblies' integrated circuits may also be used.

Note that detailled simulations designed for development support may, in certain cases, integrate the system's real operational software, if permitted by the computerized system.

2.5. Validation Phase

This phase corresponds to the last step in the industrial development cycle and its purpose is to check the conformity of the Electronic Warfare system to its specifications.

As mentioned above, the specifications of a system are no longer only defined as a set of technical specifications, but also in the form of reference scenarios which synthesize the operational requirement. The contracting authority actually intends to check that the system does meet this requirement, whose expression should match the operational use conditions as closely as possible.

The simulations which can be used at this level are of the "hybrid" type, i.e. the system itself is incorporated within the simulation loop.

The weapon system software models managed by the software kernel, allow the use of (microwave, infrared, electro-optical) hardware generators which stimulate the system thus subjected to a simulated environment: in such a case, the system replaces its model. Hybrid simulation is systematically performed in real time and must be reproducible. It does not consider the system interactions with its plaftform but its dynamic character allows subsequent flight tests to be minimized, or even dispensed with altogether.

It is generally impossible to reproduce hightly complex scenarios by using hybrid simulation, with compact installations, but similar results can be obtained by making the most of the complementary character of the main three stimulation levels, as shown below (Figure 2).

Fig. 2

Hybrid Simulation: Stimulation Types

(RF system)

Stimulation type	Integrates	Stimulation density	Main limit	Use
Anechoic chamber	The complete system	Limited number of emitters (typ.: 10) High pulse density (addition of signals in space)	Transmitter geometrical positions	Initial validation phase (limited scenarios)
"Antenna foot"	The system, excluding antennas	Large number of emitters Pulse density limited by drop out (typ.: 250 000 pulse/s)	Pulse drop out	Second validation phase (main scenarios)
Numerical stimulation	The system, excluding antennas and receivers	Large number of emitters High pulse density (no drop out)	Used to test the system's main computer only	Third validation phase (boundary test, dense environment)

2.6. Operational use Phase

During this phase, there are two types of requirements:

- Electronic Warfare system evaluation,
- support to the system operational use, programming aid in particular.

The first activity consists in investigating the system's behavior in various scenarios, in particular those which differ from the reference scenarios: the purpose is to assess the system efficiency and to guarantee its technico-operational consistency in various environments, since they are likely to evolve in the future (new threats, new battle theatres). For this purpose, one resorts to a system's behavior model insofar as delivery of such model together with the real system has been considered. This model, which is obviously specific, can not be as fine as that used during the development phase (for reasons of facility and rapidness of use) but it must have a sufficient accuracy level to allow the assessment of the system's effectiveness of interaction with enemy threats. The information output rates and the servo-control or decision loops which exploit them (typical scale: 1 to 10 ms) would be the right level of interaction to consider.

The programming aid consists in validating, by way of simulation in an Electronic Warfare center, the library data obtained by a mission planning system before routing them to the local operational level.

For this purpose, either numerical simulation (which implements a behavioral model of the same type as that used for evaluation) or hybrid simulation (which implements facilities of the same type as those used for the industrial validation phase) may be used. These methods are complementary since numerical simulation, obviously less representative, is easier to implement and offers a wider range of scenarios (if the operating time is in conformity with the operational requirements related to the programming center).

Note also that with numerical simulation, the use of a generic behavioral model may be practicable when the purpose is to get familiarized with the system's programming modes with no particular will to validate its behavior in relation with specific programming data.

It is moreover possible, through simulation, to introduce Electronic Warfare considerations at the mission planning stage.

2.7. Synthesis

The preceding paragraphs can be synthesized in the table of the next page (see Figure 3) which illustrates the three interaction levels between the weapon system and the EW system:

- global : 100-ms scale (status change logics),
- behavioral : scale ranging from 1 to 10 ms (loops, information outputs),
- detailled : pulse scale;

as well as the two above-mentioned simulation types:

- digital : software models only,
- hybrid : software models and real equipment.

Fig. 3

Synthesis of the Simulation Activities Related to Life cycle

Phase	Simulation type (numerical/hybrid)	Interaction type (global/ behavioral/detailled)	Weapon system model (generic/specific)	EW system model (generic/specific)
ELABORATION	digital	global	generic	generic
DEFINITION	digital	global	generic	generic
DEVELOPMENT	digital	detailled	generic	specific
VALIDATION	digital	detailled	generic	not applicable
OPERATIONAL USE				
. evaluation	digital	behavioral	generic/specific	specific
. programming aid	digital	detailled behavioral	generic/specific generic/specific	not applicable specific

3. THE "MESA" FAMILY OF ELECTRONIC WARFARE SIMULATORS

3.1. General

In the mid-1980s, DASSAULT ELECTRONIQUE felt the need to have global technico-operational simulation resources designed for the dimensioning of its equipment. Preliminary studies on the self-protection system intended for the future "Rafale" combat aircraft were also conducted at that time; this was thus the opportunity to integrate the notion of life cycle in tool design, which is materialized by the specifications summarized in the previous chapter.

First note that such notion as a "universal simulator" was not a good idea. The construction time required for such a system would have exceeded the life time of hardware and software items, methods and models. Moreover, its large size and complexity level would have made it a hardly controllable tool. The notion of "family" was thus prefered, since it is built around a common kernel. It therefore proved necessary to consider all the uses planned, then to carry out simulations without hindering re-use of certain parts (including the kernel) for various purposes, with the aim in mind of obtaining a large quantity of arrangements while minimizing changes.

Then, the problem of the tool generality was to be considered: it was necessary not to systematically restrict oneself to the use of specific models which might have reduced the number of scenarios likely to be simulated.
Hence, DASSAULT ELECTRONIQUE opted for generic models which could be parametered, thereby allowing the integration of any type of weapon system - already existing or to be developed - and the insertion of global expert data issued from experiments or dedicated fine simulations into the parameters of the Electronic Warfare system's model.

Thirdly, the combination of digital and hybrid simulations stressed the need for easy distinction between the weapon systems and the Electronic Warfare systems, in order to have a permanent scenario generation resource throughout the life cycle, ensuring consistency with reference scenarios.
This is why weapon system models have been endowed with a "standalone" behavior, independent of Electronic Warfare system supporting platforms and of any behavioral programming performed by the operator.

Lastly, the main difficulty of life cycle coverage consisted in managing the different accuracy (fineness) levels required. In order to remedy this difficulty, modular model design was elected: the principle of such design is based upon successive extensions of global models, therefore allowing the conformity with the required fineness level to be achieved from a common core. Thus, for a given fineness level, customized extensions of the same level are used for the weapon and Electronic Warfare systems, while adjusting the timebase accordingly with a view to correctly sample the modelled phenomena.

The MESA (a French acronym meaning environment and self-protection system modeling) concept illustrates such a family of simulators based upon a common basis of standalone generic models, which can be parametered, and are functionally modular.

3.2. The MESA Structure (Kernel)

3.2.1. Modeling

The purpose of the MESA software is to simulate the progression of one or more platform(s) equipped with Electronic Warfare systems over a terrain where ground-to-air, surface-to-air or air-to-air weapon systems have been deployed. For this purpose, MESA performs the following functions:

- modeling of friend or foe ground-to-air, surface-to-air or air-to-air weapon systems as well as their associated detection systems (early warning radars, etc.),
- modeling of interconnections (netting) between weapon systems thereby allowing the integration of the electronic battle order,
- modeling of Electronic Warfare systems (ESM/ECM),
- modeling of missiles and aircraft navigation and routes,
- simulation of operational scenarios (digitized terrains, locations, etc.),
- exploitation of results during simulation and off-line.

3.2.2. Architecture

The simulation kernel selected for the MESA family is of the combined "step-by-step/integration" type: its operating principle is based upon a timebase supplying a regular simulation step which can be parametered and which also allows untimed events to be taken into account. This meets the requirement of processing, during simulation, both continuous data (flight paths, etc.) and discrete data (mode switching, etc.).

Data structure is hierarchical (i.e. tree-structured) and allows efficient management of simulation entities by object (weapon systems, countermeasures systems, platforms, etc.).

Modularity was developped on two levels: on the first hand to allow the introduction of new modules (specific weapon or Electronic Warfare systems, particular navigation, displays, etc.) based upon the flexible principle of "interchange memory", and on the other hand, to allow matching the required simulation level:

- global status data (scale: 100 ms),
- waveforms, antenna scanning (scale: 1 to 10 ms),
- elementary pulses (scale: 1 μs).

This last point is illustrated by the Figure 4 below.

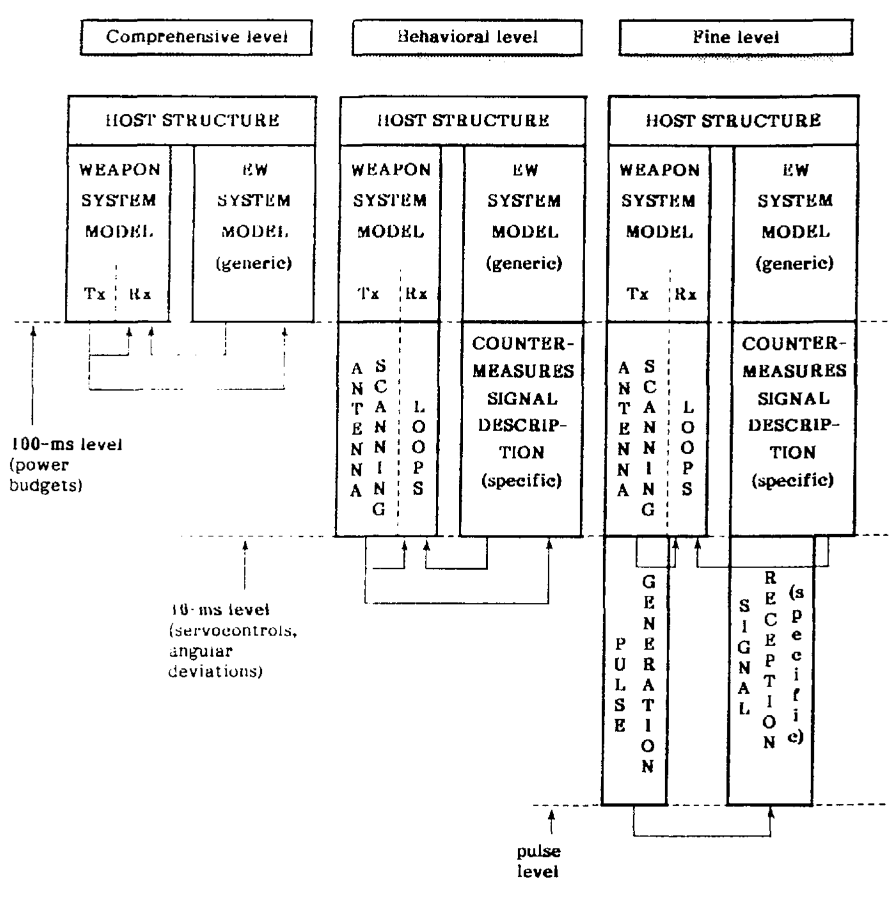
The software design relies upon industrial standards (UNIX, XWINDOWS, PASCAL, C) and is based upon dynamic memory allocation thereby ensuring efficient data management. MESA also offers a graphical and interactive man-machine interface for rapid and easy installation and use. Graphical displays allow direct results comprehension.

Besides, the simulation kernel allows the integration of real-time interactive actions: the operator may freeze the simulation process at any time in order to display technical and tactical data in real time, or modify the scenario execution (interactive platform control, for example).

Lastly, the simulation data management is structured as databases accessible through a set of menus. Parameter databases for weapon and Electronic Warfare systems, in particular, allow clear discrimination between classified data (entered by the operator) and the software itself.

Fig. 4

Simulation Levels



4. CONCLUSION

Our purpose was to highlight the essential interest of simulation in the field of Electronic Warfare, as it allows the operational requirement to be taken into account. This paper puts the stress on the necessity to have consistent tools available throughout the life cycle of Electronic Warfare systems, from the drafting of requirement specifications to operational use, to guarantee continued conformity to the technical-operational specifications. Then, we demonstrated how such an original concept as the MESA "family of simulators", developed by DASSAULT ELECTRONIQUE, has been designed to meet this requirement: i.e., as a generic, parametric and standalone common core: an interactive and modular architecture based upon open-ended computer-science standards. Since MESA had to meet the various requirements set by DASSAULT ELECTRONIQUE, who used it for its own purposes, and considering the permanent evolution resulting therefrom, MESA undoubtedly constitutes an original creation in the sphere of Electronic Warfare. MESA might thus be used, in the future, in various contexts, whether industrial or operational.

REAL-TIME E.W. TEST RANGE SIMULATOR

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1. General.

Purpose of this article is the characterization of a real-time Electronic Warfare Simulator. This system, connected with a flight simulator, can simulate test range conditions suitable for pilots and air crews battle training, through the generation of the Electromagnetic (E.M.) environment produced by a multiple threat radar geographic scenario.

Moreover, the E.W. Simulator is able to perform an E.M. closed-loop simulation, through the real-time simulation of the Electronic Counter-measures (ECM) effectiveness against the threat radars; in this way an optimum performance of all those tasks that can augment aircraft survivability is ensured. For this purpose, a mathematical model of the threat radars and of the Jammer is used, in which all the parameters characterizing these equipments are accounted for, both in transmission and in reception.

These models, that can be customized by the user through user-friendly menus, are used to develop algorithms that simulate the threat and jammer behaviour in all their operating conditions.

In general, the algorithms comprise time optimized (consequently very fast) and complex functions which require long processing times that prevent any real-time system operation. In order to achieve such a real-time capability the complex functions have been replaced by functions integrated with statistical models.

The threat radar/jammer model thus obtained provides a representation of the real environment that, despite its reduced fidelity with respect to the fully representative model, nonetheless is adequately representative for pilot training purposes. In fact, the proposed models will enable the pilot to cope with simulated situations that can be programmed with various degrees of difficulty. This unique feature makes it possible to duplicate even the most severe operating conditions, close to real combat situations.

2. Main Features.

An E.W. Simulator is basically designed to simulate, through the generation of suitable R.F. signals, the multiple threat radar environment that would be encountered by an aircraft flying over an enemy territory.

The E.W. Simulator's foremost application is the training of air crews on the use of on board ECM defensive systems. For this purpose the E.W. Simulator is integrated with a Flight Simulator so as to also account for any likely platform evasive manoeuvre.

During mission simulation the generated R.F. signals, representing the threat radars, are injected into the actual on-board equipments. In this way the pilot gains hands-on experience using the on-board control panels that provide the warning information for the proper selection of the appropriate defensive aids (active/passive ECM, evasive manoeuvres etc.) against the detected threats.

The key feature of the E.W. Simulator described herein is its ability to provide real-time simulation of both the selected countermeasures and the victim threat radar response. This consents an immediate estimation of the effectiveness of the active or passive countermeasures activated by the pilot that, combined with the proper and timely selection of available defensive techniques, ensures the achievement of high training proficiency in the employment of aircraft self-protection procedures. This basically results in the simulation of a real test range that enables pilots to train in extremely realistic environments.

This article contains a general description of an E.W. Simulator, together with examples of applications in real-time flight simulation. Moreover the application of fast algorithms used for ECM and threat radar simulation will also be described.

3. System Description and Characteristics

The E.W. simulator basically consists of:
* Host Computer;
* Operator Console;
* R.F. Signals Generator (Stimulator).

Connected with this system there are:
* E.W. Equipment and units belonging to the aircraft;
* Special H/W interfaces and on-board ESM equipment.

The E.W. Simulator interconnection scheme is shown in fig. 1. The main features of each block are as follows.

The Host Computer main function is the real-time management of the scenario, including the movement of the platforms supporting threat radars and radar mode changes, according to distance (with respect tho the aircraft) or time criteria. Moreover in the computer a data base is stored, containing the characteristics of all the R.F. emitters on the scenario.

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The Computer Console may be used both during the real-time mission simulation and during an off-line phase. During off-line the instructor is allowed to define a geographic scenario (which will be represented as a geographic map), in which he can place fixed and mobile enemy/friendly platforms (such as Aircrafts, Missiles, Ships, Tanks) and associated R.F. emitters. In the on-line phase the console is used primarly for mission monitoring. On-line and off-line phases are described in detail in the following paragraphs.

The special H/W interface is shown in fig.2. This interface may be expanded and customized according to the equipment actually used.

The on-board panels provide the pilot with a realistic representation of the E.M. environment in which he acts, on the basis of extremely reliable informations coming from the Simulator.

The R.F. Stimulator purpose is the production of the signals coming from the threats on the scenario. The Angle of arrival, the Time of Generation and the Power of each pulse are calculated according aircraft/radar relative positions, antenna pattern and E.M. characteristics. The stimulator can replicate a very high signal density environment; the generated signals contain the same PW and PRI characteristics of the simulated radars and exhibit the same modulations produced by the antenna pattern and antenna scan mode of the simulated emitters themselves.

3.1 Threat radar modelling

Radar modelling could be based on an exact mathematical model, taking into account all the parameters which characterize the radar transmitter and receiver, such as:

* Operating frequency;
* Sensitivity;
* Antenna Pattern;
* AGC Parameters;
* IF characteristics;
* ERP, PW, range gate;
* Polarization;
* Noise figure;
* MTI characteristics;
* Range/Angle discriminator parameters;
* Range/Angle Track Servo;
* Radar Operating Logic (Mode change).

Such a model requires a complex algorithm that, despite furnishing an accurate simulation of the radar's behaviour, has the drawback of requiring a long processing time, thereby preventing the system from operating in real-time.

To overcome this inconvenient, a faster model has been implemented in which some of the radar operational elements have been replaced by simpler modules, integrated with statistical functions. In this way a real-time threat radar simulation is obtained that, despite its lack of fidelity, can still provide acceptable results which are totally realistic and still suitable for test range simulation.

An example of this modelling technique is the Monopulse TTR model block diagram shown in fig. 3.

3.2 ECM Equipment modelling

A model of an on-board ECM equipment is described in order to simulate a jamming equipment; the user can customize the model by inserting his own equipment parameters through a user-friendly window environment. The parameters characterizing the model are the following:

* ECM receiver Sensitivity;
* Alarm criteria;
* Antenna Pattern;
* ECM memory loop characteristics;
* Jammer ERP;
* Jammer operating band;
* Specific countermeasure parameter for passive and active ECM.

A Deception Jammer block diagram is shown in fig.4. The deception algorithm generates the jamming pulses.

4. Simulator operating modes

Generally, the simulator features two types of work sessions: off-line operations and on-line, real-time operations.

4.1 Off-line operations

The off-line work session is used to load all the parameters necessary for mission simulation into a data base.

Generally, the off-line work session can be split up into:

* Threat/Jammer Data Base Management;
* Scenario Data Base Management. These two activities are described in the following paragraphs.

4.1.1 Threat/Jammer Data Base Management

The user loads into this data base all the parameters that are necessary for RF radar signals generation and for EW defensive systems simulation.

In particular, RF signals generation requires the following parameters:

* ERP,
* Pulse Modes (RF, PRI, PW) or CW characteristics;
* Intra-pulse Modulation;
* Emitter scan types and rates;
* Antenna polar pattern;
* Signal Polarization;
* Az and El Beamwidth.

For simulation purpose, the user will enter the values of the parameters indicated in the previous paragraphs and characterizing the on-board defensive system (both active and passive) and the threat radars that will be used during the scenario creation.

4.1.2 Scenario Data Base Management

This session is used to define:

* Scenario geographic allocation;
* Radar threats selection;
* Threat platform features (i.e.. displayed symbol, initial geographic position and attitude, route to be followed during mission simulation);
* Aircraft initial position in the scenario.

More types of platforms and threat radar systems are deployable in the scenario, including:
* Command & Control Centres;
* Radars (i.e. Search, Acquisition, Tracking etc.);
* Anti-Aircraft Artillery Systems;
* Surface-to-Air Missiles (SAM);
* Air-to-Air Missiles (AAM);
* Air Interceptors and Airborne Radars;
* Ground-mobile Systems.

The scenario also includes various types of environmental interferences that can degrade both threat radars (and therefore associated weapon systems) performances, and ECM system effectiveness (terrain masking, clutter, multipath).

More scenarios can be stored into the data base.

4.2 Mission Simulation

The mission simulation phase requires the retrieval of one of the operational scenarios from the scenario data base.

During the simulated mission, the EW Simulator is connected to the aircraft Flight Simulator by Ethernet link, receives flight data over a dedicated interface and displays the scenario evolution in terms of:
* Aircraft and Platform movement;
* Operating modes (i.e. search, track, weapon delivery) and range of threat radars.

At the same time, the RF signals representing the e.m. emissions produced by the threat radars in the scenario are generated; these signals are injected into the EW receiving system immediately after the antennas.

The RF signals are generated with a power level equal to that received by the aircraft. The following factors are accounted for:
* ERP;
* Path loss;
* Atmospheric attenuation;
* Angle of Arrival (referred to the Host Aircraft);
* Receiving and transmitting antenna patterns;
* Multipath.

During mission simulation it is possible to introduce a malfunction in order to train pilots to adopt proper emergency procedures.

Other main capabilities of the test range simulator are:
* Scenario freezing;
* Host Aircraft and platforms repositioning;
* Scenario recording and play-back.

The EW simulator could also be used to produce a form of "cooperative simulation", in which many Flight Simulators can share the same geographic scenario. This would enable pilots to train in a multi-aircraft environment as if they were in a real mission and cooperating with other friendly aircraft.

5. ECM Effectiveness Simulation

In order to simulate the effects of selected ECMs on designated threats during mission simulation, one approach could be to look up pre-stored tables reporting radar vulnerability to selected ECMs (see Reference).
In particular, these tables could be loaded with the vulnerability data of each radar referred to the various types of ECM techniques. These data would then be used in a dynamic process that accounts for both threat radar characteristics and aircraft attitude.

The procedures for preparing the vulnerability tables require the use of special tools integrated with data collected "on the field" in a real test range. Another method involves the extraction of the necessary data from a complex mathematical model. This model is used to simulate both the threat radar behaviour and the on board ECM equipments; it releases on the use of functions requiring long processing times (i.e., not a real-time process).

The above procedures, also furnishing a real-time simulation of the ECM effectiveness, have the drawback to require high-cost off-line operations which, further, have to be repeated each time it is necessary to update the tables (e.g., to account for new types of threats and/or ECMs).

To by-pass these problems, a mathematical model simulating the threats and the jammer is implemented in such a way that it can be used on a real-time basis and that exploits both a number of functions used in the original model and others replaced by statistical functions (see fig.5). This makes it possible to simulate ECM effectiveness without having to use vulnerability tables.

The whole system would therefore operate on a real-time basis. Also, the use of parametric algorithms enables the user to update the characteristics of the equipment to be simulated. Paragraph 6 illustrates an example of ECM effectiveness simulation.

6. Example of ECM Effectiveness Simulation

The example used to evaluate ECM effectiveness is based on a model of an RGPO (Range Gate Pull Off) + AGPO (Angle Gate Pull Off) algorithm (see Fig. 6).

The model described in the previous paragraph is used to simulate the jammer and the threat radar receiver, where the parameter values are user-defined. The algorithms used for angle and range gate stealing, together with those used for jammer effectiveness evaluation, which in the original algorithm would require such long processing times as to prevent any real-time performance, are replaced by statistical functions based on Montecarlo type algorithms. The use of statistical functions is illustrated in Fig. 7. The probability curves in fig.6 show (as a function of time) the success probability of the RGPO and AGPO techniques starting from the instant in which the technique is activated.

The shape of the above-mentioned curves, as well as the assigned maximum probability value and deception program duration, depends on the J/S ratio, jammer and threat radar receiver characteristics .

Successful break-lock conditions can be determined for each instant (with respect to selected starting time) either by simple decisional algorithms or by a Montecarlo method that compares the resulting number with the probability that in that same instant the deception process is successful.

The denied or successful break-lock attempt directly affects the RF signal generator; for example, it can introduce an angle off-set in the generated RF signal that corresponds to the deceived threat emission. As a result, the pilot in the flight simulator cockpit receives an immediate indication of the jammer's effects on the threat and he is prompted to make the necessary decisions in real-time; if, for example, the selected ECM technique was unsuccessful, the pilot can select another type of ECM (and therefore to launch chaff or other items) and/or conduct evasive manoeuvres.

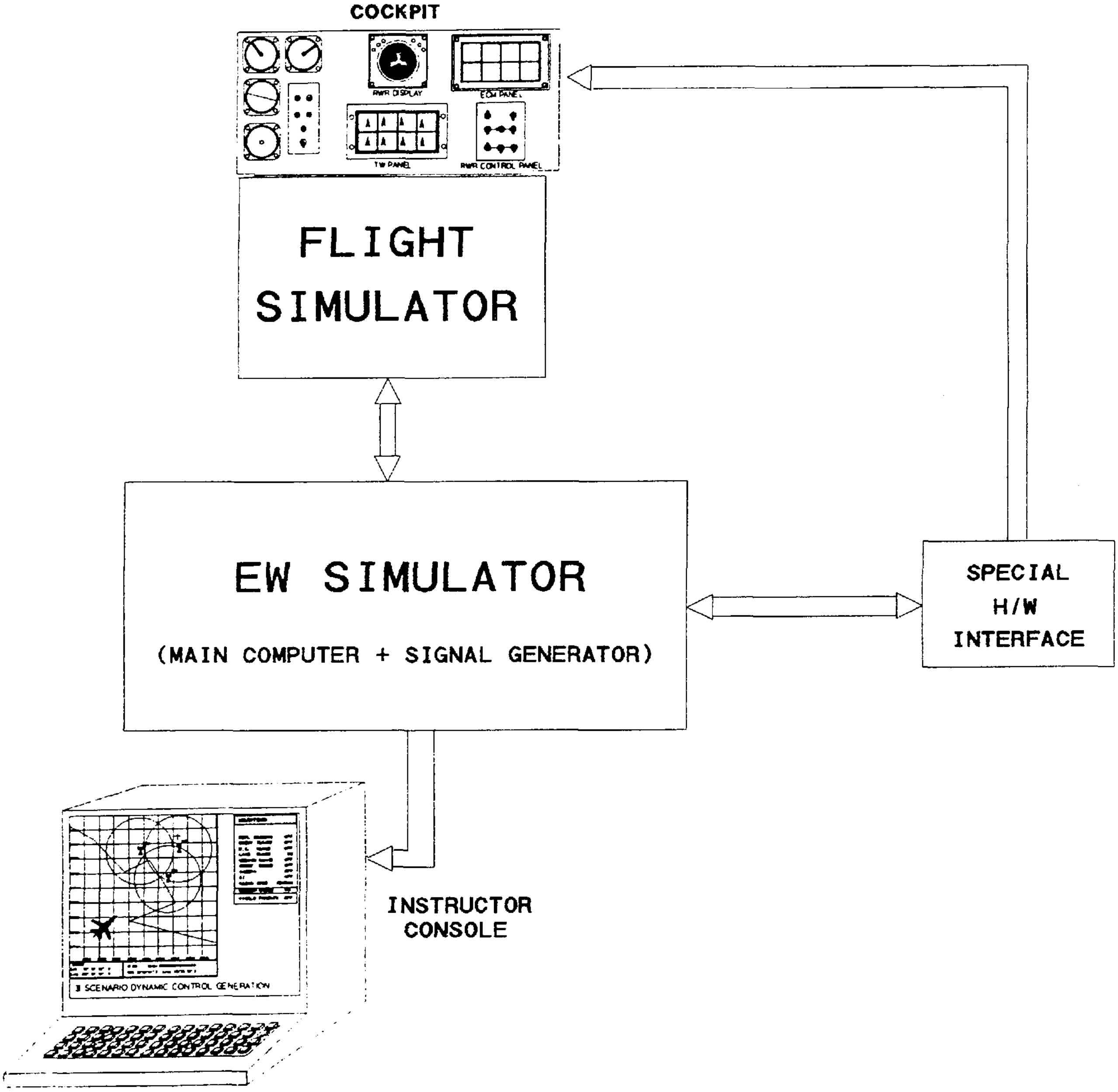

FIG.1: E.W. SIMULATOR INTERCONNECTION SCHEME

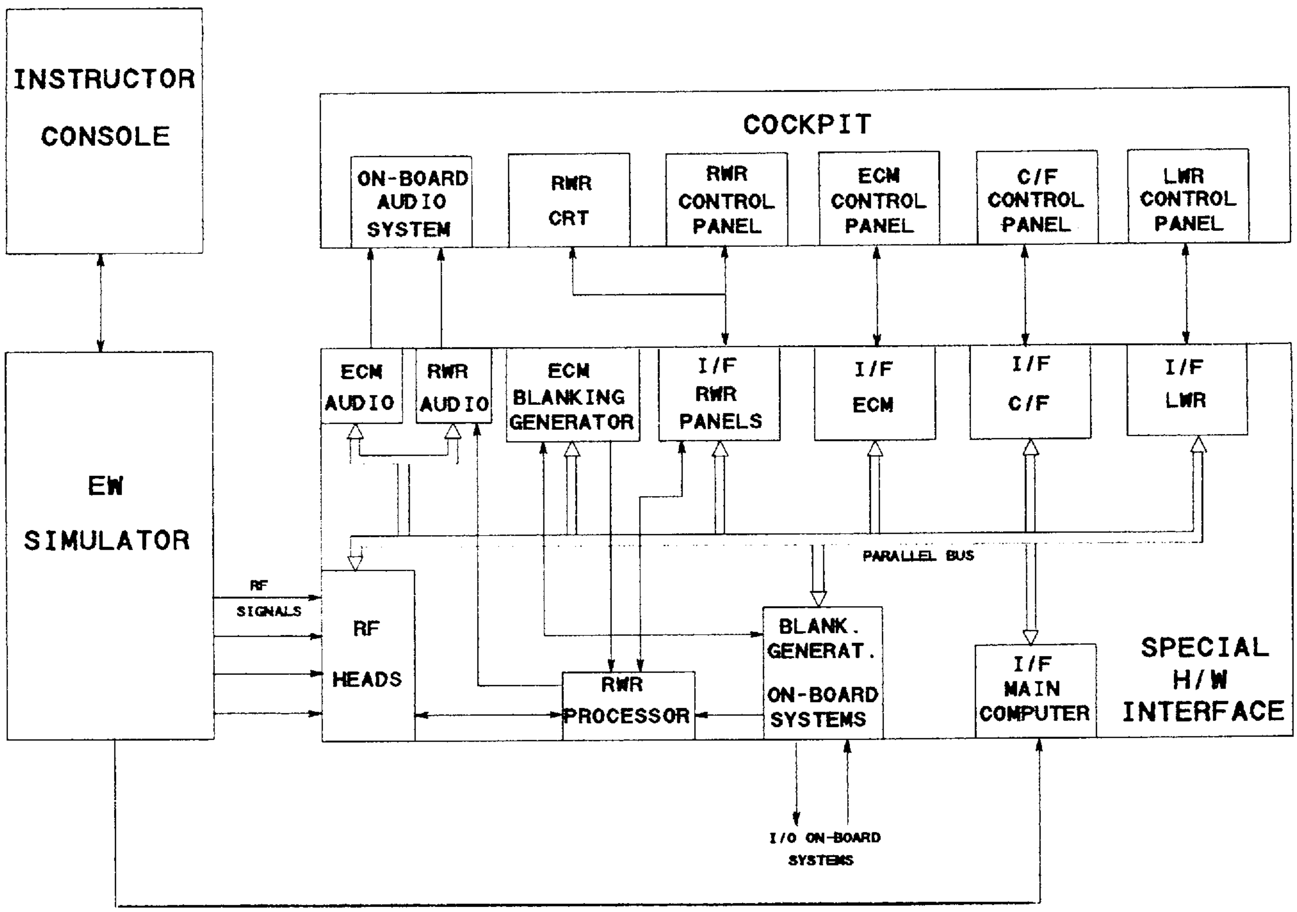

FIG.2: SPECIAL H/W INTERFACE BLOCK DIAGRAM

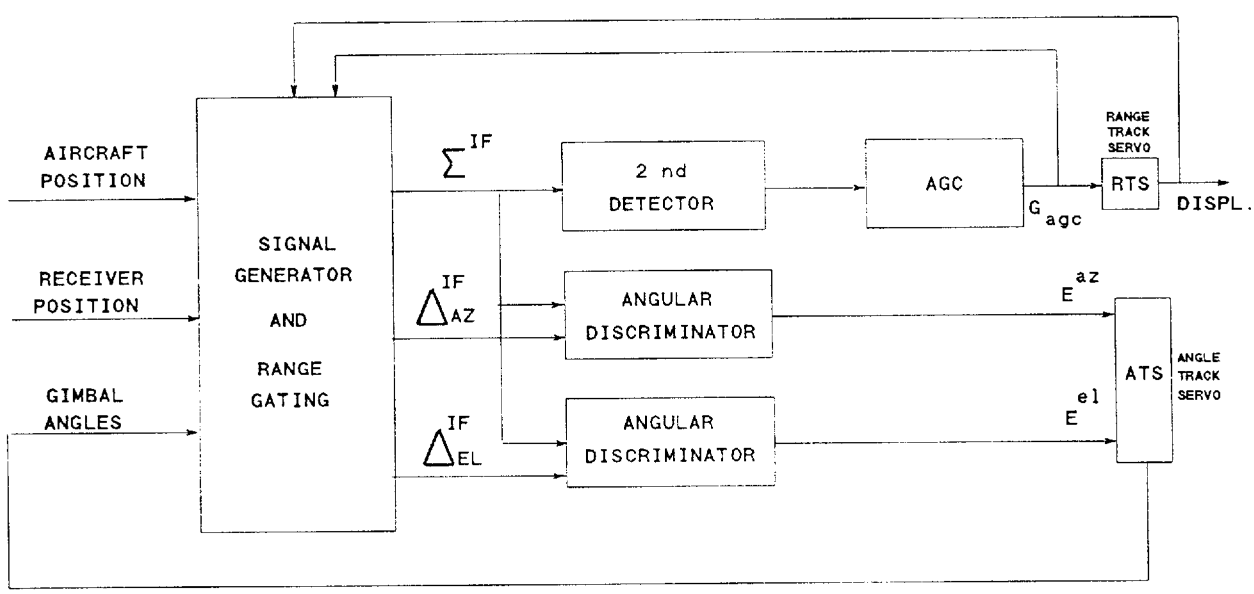

FIG.3: BLOCK DIAGRAM OF TTR MONOPULSE RECEIVER SIMULATION

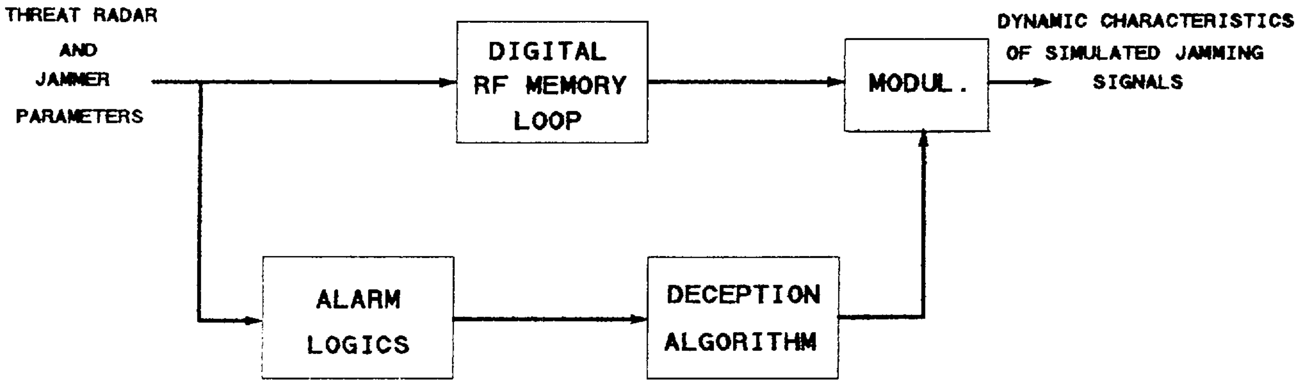

FIG.4: JAMMER FUNCTIONAL BLOCK SCHEME

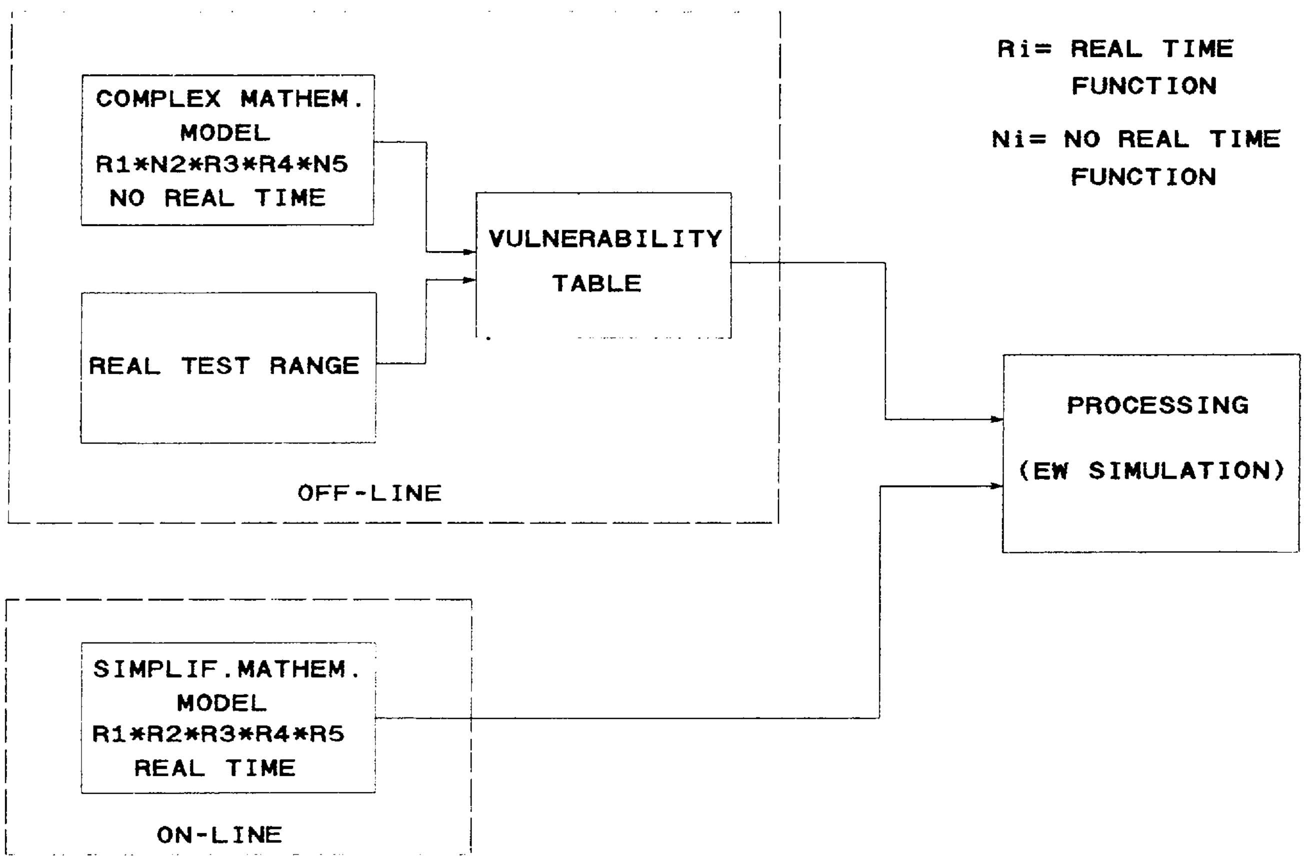

FIG.5: OFF-LINE AND ON-LINE OPERATIONS

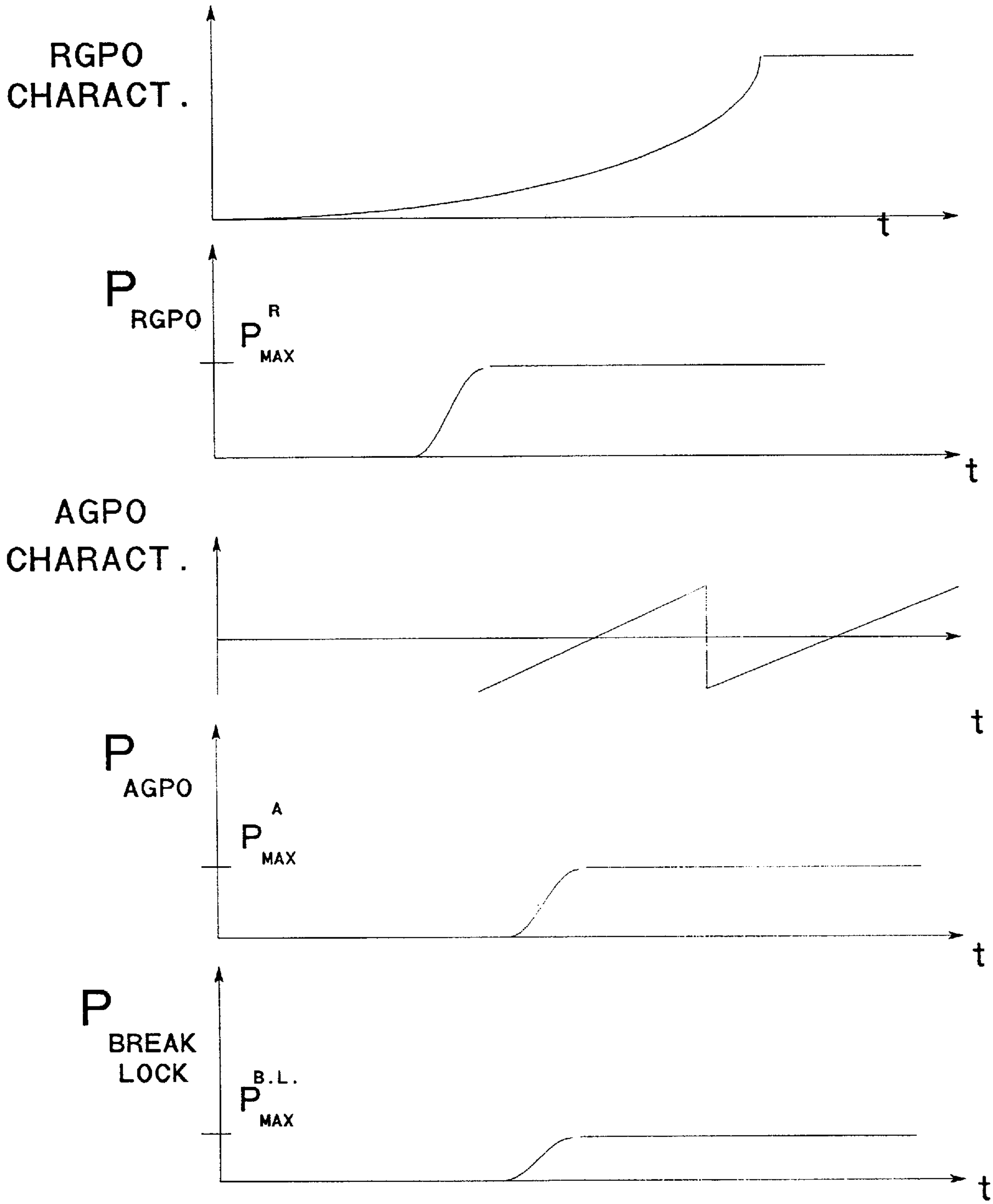

FIG.6: RGPO-AGPO CHARACTERISTICS AND BREAK-LOCK PROBABILITY

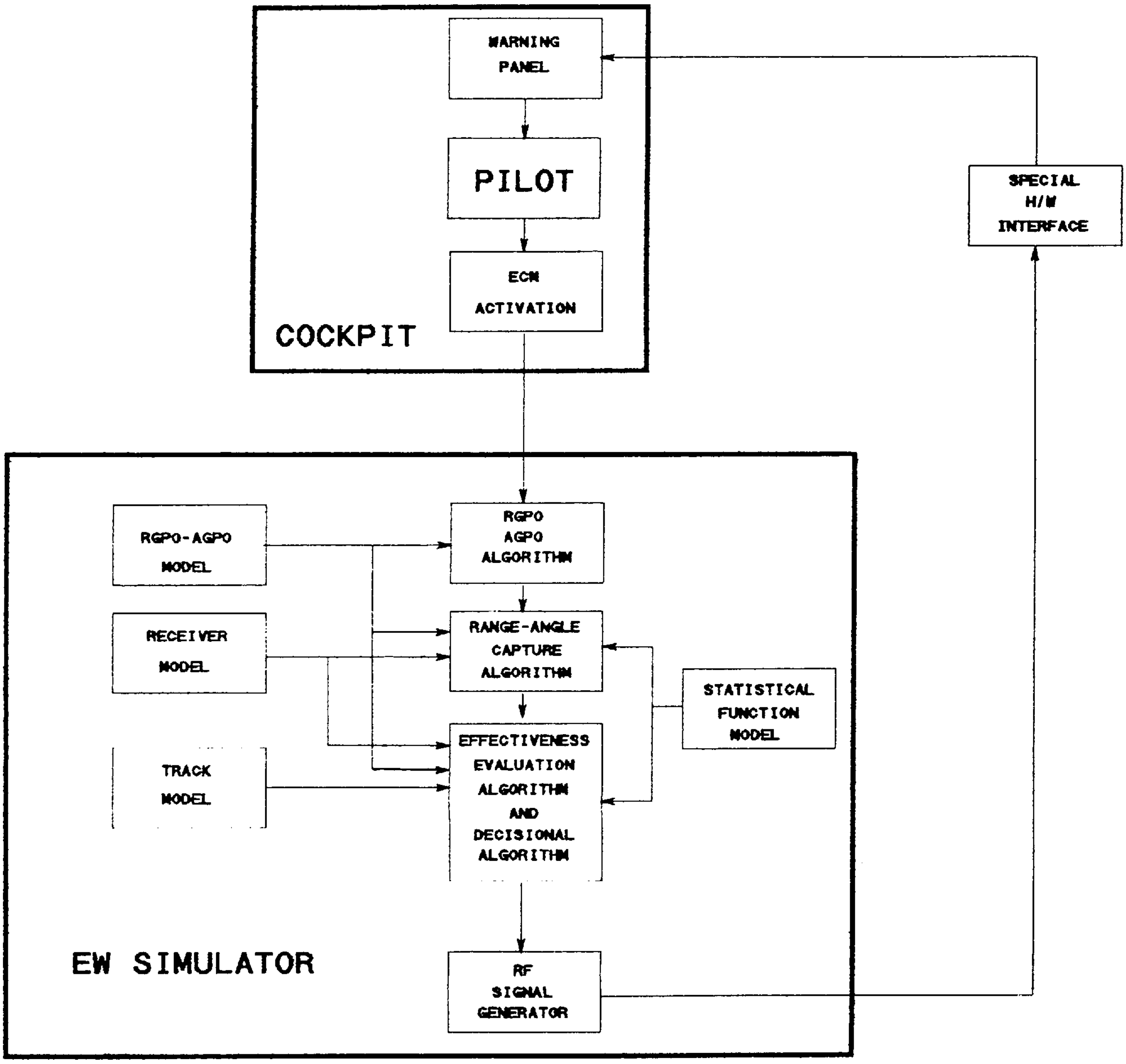

FIG.7: EXAMPLE OF COUNTERMEASURE EFFECTIVENESS SIMULATION

ANALYSTS' WORKBENCH

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China Lake, CA. 93555-6001, U.S.A.

ABSTRACT

Analysts involved in the study of missile performance and effectiveness require telemetry data and simulations to conduct significant analyses. As a result, these analysts are inundated with the data generated. Using an exclusively numerical format, analysts cannot effectively interpret these valuable data.

Analysts need an alternative to numbers. They need the ability to visualize these data and tools to answer key questions, such as

Did the subsystem function satisfactorily?
Did the subsystem function at the proper time?
Did any evidence of unexpected or marginal subsystem performance exist?

The Analysts' Workbench, developed by the Naval Air Warfare Center Weapons Division (NAWCWPNS), China Lake, provides analysts with the ability to interactively visualize flight tests, laboratory, and digital simulation results. The Analysts' Workbench supplies many of the tools needed to answer the key questions listed above. These abilities are imperative to (1) ascertain the integrity of the analyses, (2) provide insights into subsystem performance, and (3) share those insights with others.

INTRODUCTION

Electronic warfare hardware and missile system analysis have been conducted traditionally by means of strip charts and computer printouts. Analysts manually evaluate the strip charts for anomalies for each data parameter on the checklist and write the results on charts for data-entry personnel to place into the database. After completing the evaluation procedure for each item on the test plan, the analyst conducts a statistical analysis to detect trends within these data. After all of the analyses are complete, a report is generated and delivered to the appropriate program office.

Current methods are an inefficient use of the analyst's time and talents. The analyst spends a large portion of the time just searching for the data rather than interpreting them. The Analysts' Workbench provides the tools required to integrate, consolidate, and visualize the data so the analyst can conduct a complete and full analysis within a reasonable time.

BACKGROUND

Clearly the new technologies and software tools that have been, and are being, developed in computer graphics, scientific visualization, and image processing are having important implications within the defense industry. These technologies, such as the Analysts' Workbench, are focusing on communication between the computer and analyst, between analyst and analyst, and from analyst to management. While some of the users of the Analysts' Workbench are good at processing visualization material, others find this area one of great difficulty. The reason for this difficulty is that some people are visual thinkers and others are verbal thinkers.

Leonardo da Vinci's emphasis on imitating nature and analysis through visualization served him well—to learn and communicate by doing instead of reading—to learn and communicate by seeing and experimenting instead of following traditional memorized algorithms. With the profound influence of computers of all kinds, we are now part of a new era. The skills of the Renaissance thinker, such as Leonardo da Vinci—recombining the arts and sciences to create elegant and integrated solutions to urgent and complex problems, are required to cultivate the different skills required in the evolving computer age.

Tom West, author of the *The Mind's Eye* observed that our schools have taught the basic skills of a medieval clerk, i.e., reading, writing, counting, and memorizing. He forecast that eventually the best clerks would be software and machines. Currently, designers of computers and software are tasked with

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bridging the gap between visual and verbal thinkers. Visual-spacial abilities are considered to be a definite form of intelligence by many psychologists. Some neurologists believe that an inverse relationship exists between visual-spacial abilities and conventional verbal and academic abilities. Very highly gifted visual thinkers apparently display traits of those with dyslexia or learning disabilities (Reference 1).

The late Harvard neurologist Norman Geschwind was interested in the apparently paradoxical pattern of high visual talents with verbal difficulties. He observed that in recent years, dyslexics have often displayed considerable talents in many areas, e.g., Thomas Edison and Albert Einstein. In addition to adjusting, in some instances, dyslexics have contributed greatly to the very fabric of our modern world. He suggested recent studies have shown that many dyslexics possess superior non-verbal skills relating to art, architecture, engineering, medicine, and science (Reference 2).

Today, much emphasis is placed on Concurrent Engineering and Total Quality Management efforts. Now, apparently the new buzzword is Collaborate Engineering. However, not much joint work, communication, or collaboration is in evidence. The technical and cultural aspects of these efforts require large amounts of communication. The right-brainers and left-brainers, the verbal thinkers and visual thinkers, do not have a common language to bridge these communication barriers. The challenge for software and computer developers is to design, produce, and integrate a new era of software bridges.

The Concurrent Engineering Research Center's (CERC), at West Virginia University, Morgantown, W. Va., work with Defense Advanced Research Projects Agency's (DARPA's) Initiative on Concurrent Engineering (DICE) Program emphasized six different software bridges. While these software bridges may not represent a panacea, they are providing some computer software and hardware designers with a focus and direction. The following table lists each area of focus, and a brief description of the goals.

Focus area	Description
Network collocation	To overcome the barriers between remotely located experts and their tools
Constraint management	To ensure a common focus and consistency between experts working in parallel
Information sharing	To enable seamless access by different disciplines to results as they are developed
Corporate memory	To support continuous improvement based on the decisions and explorations of the past
Framework and tool integration services	To exploit techniques to embed tools into the architecture so that they can inter-work with each other and the architecture services
Merging with legacy data	To exploit existing databases without reorganizing data or rewriting existing programs

The remainder of this paper briefly discusses previous efforts of the Analysts' Workbench and the new direction we are taking to address the visual-thinker and verbal-thinker paradox and to capitalize on developments of the aforementioned software tools.

PREVIOUS WORK AND FUTURE ENHANCEMENTS

In previous work, the Analysts' Workbench focused on obtaining the desired frame rates of the graphics interactions and on the determination and implementation of the most effective tools. This focus was intended to help the analyst gain access to and insight into the data. The majority of these tools was developed at NAWCWPNS, which did not have the resources available to maintain development. Furthermore, the tools required massive redesign as computer technology moved forward. A decision was made to replace these tools with commercial applications where privately owned companies could keep up with technology enhancements, ensuring portability, and NAWCWPNS could focus on implementing the goals of CERC's six software bridges. Future enhancements of the core software packages were abandoned by NAWCWPNS.

The following sections briefly describe the tools in the Analysts' Workbench, some of the problems encountered by the users and developers, and the future direction of the Analysts' Workbench.

DATA-EXTRACTION AND -REDUCTION TOOL

The data-extraction and -reduction tool's objective is to transfer telemetry data acquired during real and simulated flight tests from the raw telemetry into a usable format for the analyst. Dealing with this "big data" is a laborious and time-consuming process. The format of the data varied for each type of weapon system. Standardization of the format was impossible because of the different telemetry requirements, and customized software was required for each weapon system. Additionally, the data arrived on a variety of tape devices—8-mm, 4-mm, QIC 150, QIC 60, 9-track, and analog. The analog tapes required additional processing to decommutate the data. Although inevitable, this problem did make using the data-extraction tools difficult and required a dedicated programmer to maintain the changes throughout the test and evaluation stage of the program. However, this problem did not preclude using a standardized look and feel of the graphical user interface (GUI), such as motif. Currently, efforts are underway to hide the details of the data-extraction and -reduction tools under a GUI common among weapon flight test and simulation tools.

DATABASE TOOLS

The heart of any analysis software package is its ability to access and process data. The previous database approach limited analysts' ability to access the data. The software used the file structure of the Unix Operating system to store each separate test. The software then altered the current path in the file structure and used pop-up menus to access the data. This approach was not structured to use the new technologies needed to capitalize on CERC's recommended software bridges. The Analysts' Workbench needed a relational database software engine to implement the required framework and tool integration services. A relational database was required to exploit existing databases and maintain a corporate memory of the system's test and evaluation results. The Oracle relational database is being incorporated into the cost, operational, effectiveness, and analysis (COEA) studies and will soon be wrapped into the Analysts' Workbench.

By using the Oracle software package developed by Oracle Corp., Redwood Shores, Calif., as the engine for the framework and integration service, access to telemetry data for trend analysis will be faster and more reliable and documentation of subsystem performance requirements for each test will be easier to maintain. The commercial software package Asterix, developed by Applix, Inc., Westboro, Mass., which supplies a spreadsheet, graphical editor, and word processor, is being integrated to access the Oracle database engine to conduct what if and why studies. We anticipate that these tools will be fully integrated by next summer.

ELECTRONIC STRIP CHART TOOL

Analysts like to use strip charts and numbers. However, spreading a strip chart over a conference table is not the most efficient means of evaluating the data. The electronic strip chart depicted in Fig. 1 is used to display a time segment of four selected telemetry channels. Using the video tape recorder (VTR) controls, the analyst can move time by pressing REWIND, FFWD, STEP>, <STEP, PAUSE or PLAY. This time is stored in shared memory for the other tools within the Analysts' Workbench to access.

OUT-THE-WINDOW TOOL

The out-the-window tool provides a visual representation of the missile flight parameters, subsystem characteristics, and physical test environment, Fig. 2. By using the visual representation of physical and infrared environment, communication of the complex relationships between the target, environment, and the missile are possible.

The previous out-the-window tool was unable to use the new technologies available for computer-image generation. These technologies include texture mapping, hierarchical database traversal, instancing, and real-time anti-aliasing. The tool was limited to the visual spectrum, and the visual database could not be modified easily, except by a few graphical programmers. Current efforts are underway to use commercial software packages to generate and maintain these scenes, which can provide a variety of different spectrums for visual representation.

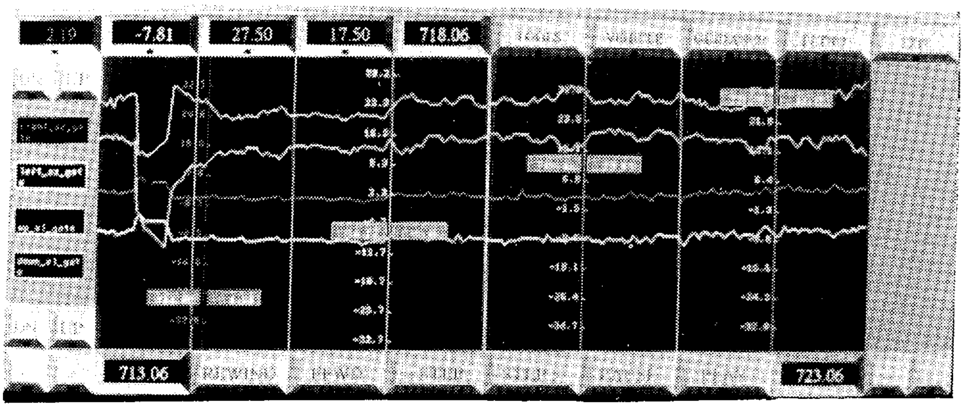

Fig. 1. Electronic Strip Chart.

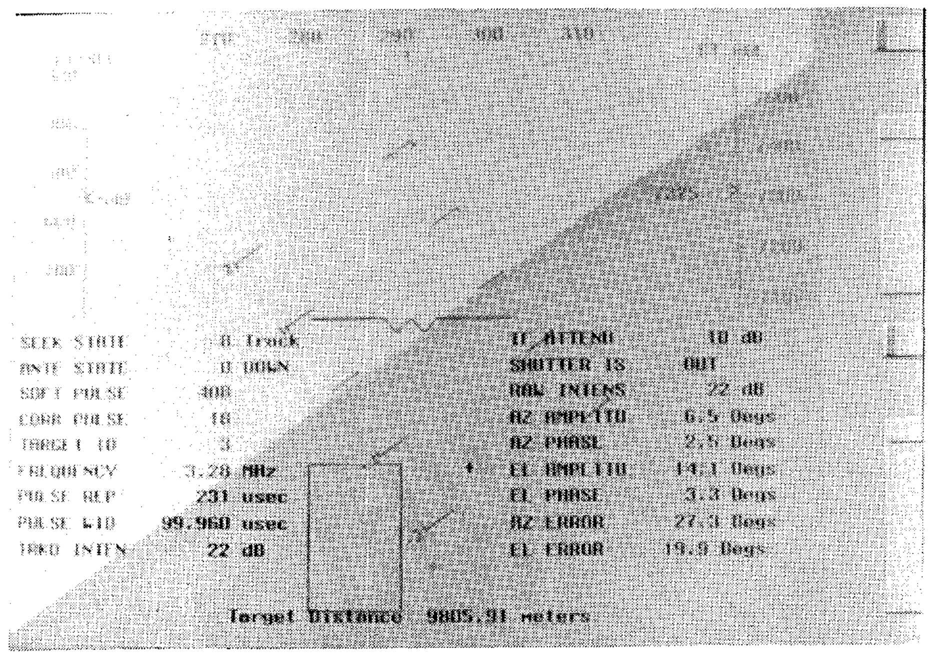

Fig. 2. Out-the-Window View.

The Multigen Software Package, developed by Software Systems, San Jose, Calif., is used to generate the visual hierarchy database. This software package is capable of importing digital terrain elevation data, digital feature analysis data, and data-transfer format models, and images to represent the physical environment.

The IRGen Software Package, developed by Technology Service Corp., Santa Monica, Calif., is used to modify the visual hierarchical database to an infrared database. This software uses the material characteristics of the physical environment, the time of day, atmospheric conditions, and seeker characteristic to modify the visual scene database to an infrared scene database.

The Gemini Simulation Package, developed by Gemini Technology, Inc., Irvine, Calif., is used to traverse the visual or the infrared scene database. The GVS Simulation package, obtains time, space, position information (TSPI) and telemetry data at the required rate to view the out-the-window scene. In addition, this software provides heads-up display (HUD) symbology to depict subsystem parameters.

PLAN VIEW TOOL

The plan view tool provides a three-dimensional perspective of the missile flight test on the test range. An icon of the test vehicle depicts the location, altitude, and seeker field of view. Icons of the targets and key features are also displayed (Fig. 3).

Using this tool, the analyst can see a perspective view of the missile, seeker range, and field of view. These features provide the analyst with a better understanding of the seeker interactions with the target and other targets within the test area.

Efforts are currently underway to use the Gemini Simulation Software to replace this tool. Future versions of this software will depict transparent target characteristics overlayed on the plan view. We anticipate that this software will be completed and integrated into the Analysts' Workbench by February 1994.

DATA VIEW TOOL

The data view tool provides analysts with bar charts, strip charts, dials, histograms, and discrete indicators to monitor key subsystem parameters (Fig. 4). When a parameter does not meet expected performance characteristics, the analyst is alerted with audio cues.

This tool is currently being replaced with the Scenario Toolkit and Generation Environments and Virtual Application Prototyping System software package, developed by Virtual Prototypes, Long Beach, Calif. We anticipate that this software will be completed and integrated into the Analysts' Workbench by June 1994.

MESSAGE MANAGER TOOL

Many weapon subsystems communicate with other weapon subsystems over a communication bus. Analysts typically like to view the message traffic over these buses. The message manager tool displays this message traffic and the contents of a user selected message. This tool is synchronized with the other tools in the Analysts' Workbench and enables the analyst to monitor individual words, bytes, and bits of the selected message type. This software is currently operational and in use.

AUTOMATIC REPORT WRITER

The automatic report writer is a documentation package customized for an individual user requirement (Fig. 5). The analyst interactively accesses standardized forms that guide the analysis and fulfill the laborious documentation requirements.

This tool is being replaced with the Asterix word processing package and the Oracle database forms software. This enables the analysis to be stored with the data, providing easy access for future trend analysis, and provides a method for saving corporate memory. We anticipate that this software will be completed and integrated into the Analysts' Workbench by August 1994.

DIGITAL MEDIA TOOL

The digital media tool provides both audio and video for the Workbench (Fig. 6). Normally for a live flight test, live video and audio are recorded. The digital media tool allows flight test video to be seen and audio to be heard. The tool synchronizes the video and audio data with the telemetry data on the Analysts' Workbench. This synchronization allows an analyst to see and hear the test as well as annotate the flight test subsystem performance characteristics. Other analysts may then review these data from the database, replay the test, and get a visual and verbal explanation of the test results. This technology enables the retention of corporate memory as well. We anticipate that this software will be completed and integrated into the Analysts' Workbench by February 1994.

CONCLUSION

The products of the Analysts' Workbench are continuously improving. The integration of commercial software packages, customized software, and the six software bridges are helping the analyst understand, analyze, and communicate subsystem performance characteristics. The visual, audio, and verbal tools are providing insights into the data. The database and documentation tools will provide a method of saving corporate memory. The framework of the Analysts' Workbench provides expandability and room for future enhancement.

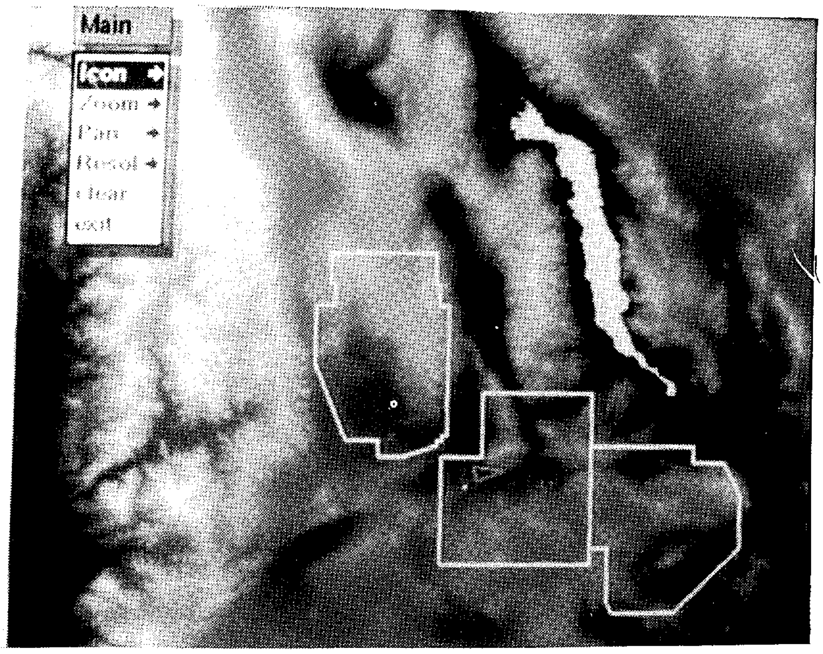

Fig. 3. Plan View Tool Display.

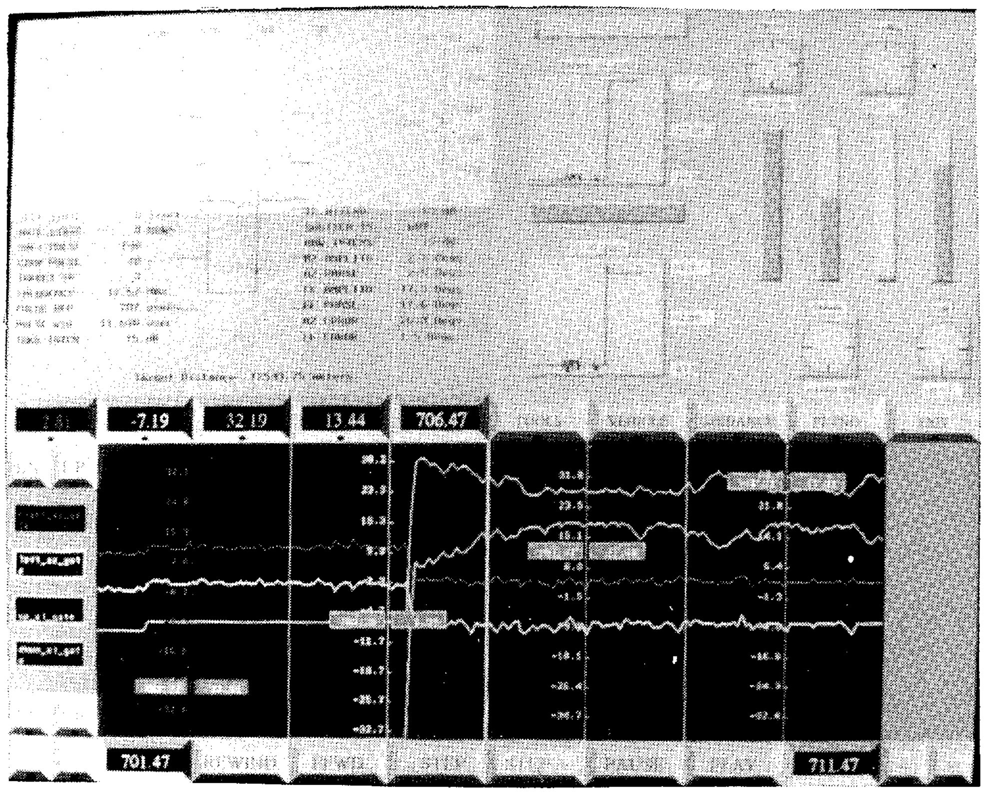

Fig. 4. Data View Tool Display.

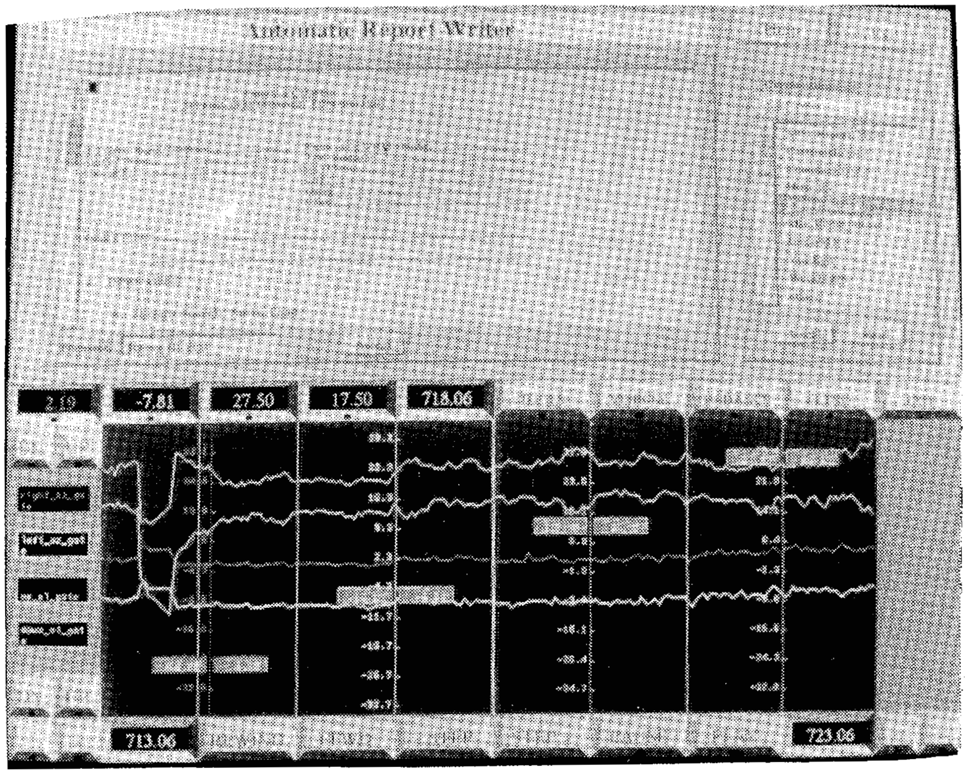

Fig. 5. Automatic Report Writer.

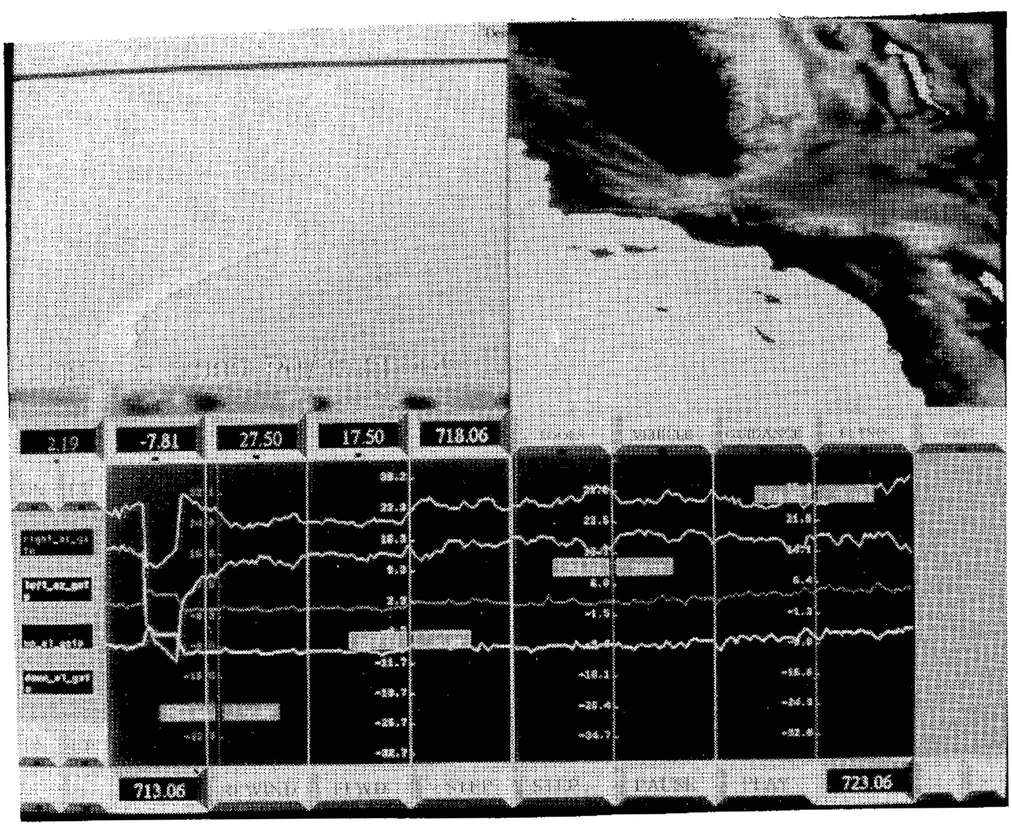

Fig. 6. Digital Media Tool.

REFERENCES

1. Thomas G. West. *In the Mind's Eye: Visual Thinkers, Gifted People With Learning Difficulties, Computer Images and the Ironies of Creativity.* Prometheus Books, 1991.

2. Norman Geschwind and Albert M. Galaburda. *Cerebral Laterialization: Biological Mechanisms, Associations and Pathology.* Cambridge, Mass., Massachusetts Institute of Technology Press, 1987.

LETHALITY CALCULATIONS IN AIR DEFENSE SUPPRESSION

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ABSTRACT
This publication contains an explanation of mathematical computer modeling for lethality analysis of antiradiation missile weapons attacking air defense radars. The appendixes contain the mathematical formulations that are now in use at the Naval Air Warfare Center Weapons Division, China Lake, Calif.

NOMENCLATURE

AAA	anti-aircraft artillery
CEP	circular error probable
DOF	degree of freedom
GPBP	General Point Burst Program
JMEM	Joint Munitions Effectiveness Manuals
NAWCWPNS	Naval Air Warfare Center Weapons Division, China Lake, Calif.
OSAST	Ordnance System Analysis for Surface Targets
P_k	probability of kill
P^3I	preplanned product improvement
RGC	range gate cutoff
SAM	surface-to-air missile
SDI	Strategic Defense Initiative

INTRODUCTION
The primary task of a missile is to eliminate a threat. This threat could be any man-made object that would be an obstacle to the goals or policies of the North Atlantic Treaty Organization. In the case of air defense suppression, the threats are surface-to-air missile (SAM) and anti-aircraft artillery (AAA) sites.

The lethality of a weapon in air defense suppression involves the ability of antiradiation missile systems to destroy enemy radars. Unfortunately the cost in both time and resources does not allow us to analyze the missile system by launching it against every target in every situation. Thousands of test missiles and every possible target and condition are simply not available. The other problem with this concept is implementation; the missile must be built and therefore modifications are much harder and much more expensive.

Simulation is the solution to this dilemma. The simulations are in both the physical world and the abstract world of computer modeling. Physical world simulations include an actual radar that gives a close approximation of the threat radar characteristics. Simulating a threat radar in the physical world is quite expensive. If the missile guidance, aerodynamics, and seeker work well, then the simulated threat radar could be available for only one shot (even with no warhead in the missile). Fortunately a mathematical computer model of a threat radar is less expensive to create, is capable of withstanding innumerable impacts, and takes up less space. However, computer modeling does not completely eliminate the need for field testing.

A computer model is only as good as the information provided by the designer. Problems may occur in the way in which the lethality analysis is performed. Intelligent methods must be used in computer simulation to ensure the validity of the results. This report discusses the simulation methodology and tools used by the Naval Air Warfare Center Weapons Division (NAWCWPNS), China Lake, Calif., Weapons Simulation and Data Analysis Branch to perform lethality analysis.

The Use of The 6 Degree of Freedom Model In Lethality Analysis
The classical method of doing lethality analysis starts with a 6 degree of freedom model (6-DOF). The 6-DOF model simulates the flight of the missile; predicts the down range position, cross range position, and altitude of the missile; and also predicts the pitch, yaw, and roll. If the 6-DOF model is written well, it will accurately predict the exact position of the missile, given particular stimuli. The stimuli could be thrust, gravity, air density, winds, weather, or guidance and control inputs. If the 6-DOF model is complete, it will also be able to use information that the seeker would obtain from both the threat and the friendly radar environments.

The 6-DOF model is run to determine the exact terminal conditions for the missile encountering the target. Once the terminal conditions are found, a fuze model is run to determine where in space the detonation of the warhead would take place. Then the probability of kill (P_k) model is run to determine the likelihood of the missile killing the target, given these particular terminal conditions. The usual radar kill criterion is that the radar will not be able to radiate for at least 4 hours.

The number of 6-DOF runs needed to accurately determine the lethality of the missile system is not easy to define. The position of the warhead at detonation is a function of the fuze and of the terminal conditions. The number of variables that should be used in the 6-DOF model can be many, and each variable may change the terminal conditions. Currently, the concept of either letting the 6-DOF model run until the integrated P_k becomes asymptotic or until a closure seems certain, has been the rule of thumb.

There is a simple way to calculate a P_k with minimal use of a 6-DOF model. A 6-DOF model is still needed to determine

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distributions, the range of terminal conditions, determination if the missile can engage the threat, and circular error probable (CEP), based on given parameters and seeker abilities. However a 6-DOF model is not needed when P_ks are developed. The only information needed from the 6-DOF in calculating a P_k is the distribution of terminal conditions. Information about where the seeker thinks the target is, the command and guidance input into the aerodynamic surfaces, and other such information is not used. The P_k developed in this technique only addresses the raw ability of the warhead. Some missiles determine where the warhead will burst by where the missile seeker believes the target to be located. If this is the case then we need only to select the proper P_k from the population.

The 6-DOF model gives the lethality analyst the distribution of the missile position and orientation relative to the target after many runs are obtained. For each run of the 6-DOF model, a P_k run is performed with the particular terminal conditions. This procedure gives a P_k based on the position and orientation that the 6-DOF model gives for the warhead. The end result of this procedure is an analysis based on that particular 6-DOF run. If the 6-DOF model is changed, then the P_k analysis should be recalculated, because the P_k is strictly determined based on the 6-DOF run result.

The use of the 6-DOF model in the determination of the detonation point and orientation obviously determines the lethality one will obtain. To minimize dependency on the 6-DOF model, one may use the following procedure.

METHOD OF LETHALITY ANALYSIS WITH MINIMAL DEPENDENCE ON THE 6 DEGREE OF FREEDOM MODEL

Pre-analysis is performed to determine the effects of terminal dive and azimuth angles, along with terminal velocity, on P_k. The determination of the number of terminal conditions must be used to provide the size of the P_k database for a 6-DOF distribution overlay.

The database is a set of terminal velocities and terminal angles that make up the total possible range of conditions. Each element of the database is made up of several parallel trajectories along the terminal dive and azimuthal angles at the terminal velocity. A separation distance between trajectories is then selected. All measurements are made in a plane perpendicular to the missile path. This series of trajectories forms a grid of loci. Analysis may be performed to determine the maximum size of the grid to include all non-zero P_ks. This grid represents all possible interesting trajectories along a given dive angle, azimuthal angle, and velocity (trajectories that result in zero P_k because they are beyond the range of the warhead are not "interesting").

For each trajectory in a grid, a fuze program is used to obtain a fuze point. It is possible to set a detonation point every few feet along each trajectory to set up a "perfect fuze" study. The "perfect fuze" study is discussed in more detail later. Once a fuze point for each trajectory is determined, a P_k may be determined using a P_k model.

We now have a set of loci with associated values. To determine weapon system effectiveness, the associated values must be integrated with the accuracy of the missile. There exists a probability that the missile will fall in the area defined by the loci of the grid trajectories, given the dive and azimuthal angles and terminal velocity (this distribution is known as the overlay). This probability is the weight value for each P_k. To determine the overall effectiveness, the expected value of distribution is calculated as follows:

$$E(Y) = \sum_y y\, p(y) \quad \text{or} \quad E(Y) = \int_{-\infty}^{\infty} y\, f(y)\, dy$$

Although the distribution of missile trajectories is a continuous distribution, the use of a digital computer and the methods that must be employed forces the discrete method. Thus, for every locus in the grid there is a probability of occurrence. The expected value of missile effectiveness given particular dive and azimuthal angles and a particular velocity is the sum of the products of P_k, given the detonation position and the probability of the missile having that trajectory.

In much of the analysis work that the NAWCWPNS Weapon Simulation and Data Analysis Branch performs, the 6-DOF model does not yet exist (or does not have the fidelity to give an accurate probability distribution of missile miss distances to target). If no reliable probability distributions exist, a bivariate normal distribution is assumed. The bivariate normal distribution is assumed because it is the most general and the most information is known about it. A missile system's effectiveness is usually determined using a specified CEP.

The CEP is defined as the " . . . radius of the circle centered at the mean which contains 50% of the shots . . . " (Reference 1). This circle must be in a plane perpendicular to the trajectory of the missile. The CEP is a measure of guidance and kinematic capability of the missile system. The only rational method is to measure the CEP in a plane that is perpendicular to the missile flight path (which would be a true measure of the guidance and kinematic capability). CEP measured in the ground plane is useful for dumb bombs and other such items, but not for smart weapons.

Once a CEP is selected, the probability of the missile's being within a particular distance from the target may be simply determined. Assuming that the distribution is bivariate normal, the probability that the miss distance is less than a particular radius, r, may be found by:

$$1 - e^{-\frac{r^2}{2s^2}}$$

where s^2 is the sample variance.* This formula is derived in Appendix A. The determination of the probability that the missile trajectory is between two particular radii is simply the probability that the missile is within r - r', where r is the radius of the outer circle and r' is the radius of the inner circle. The relationship between CEP and the sample variance is $r = \sigma\sqrt{2 \log_e(2)}$ where r is the CEP and σ is the population variance (in our work we may use s for σ). This formula is derived in Appendix B.

The probability that a missile will be x distance away from the target does not state in which direction. The probability covers everything within a particular radius from the target. To determine which locus to use, one may determine the number of loci in the disk, divide the probability by this number, multiply each locus P_k by the result of the division, and then add all the products. Or we may multiply the

*Do not confuse σ with s. σ is the population variance where s is the sample variance.

probability of the miss distance by the average P_k for the ring. These two methods are equivalent.*

If examination of the results of the lethality of the missile system using different CEP values is considered, then the different weighting factors for each ring are calculated and the new integration is performed. This is done without recalculation of the P_ks or the fuze points. When a 6-DOF model gives the distribution of miss distances, use the weight factors given by the distribution and then perform the integration, again without recalculations of the P_ks or the fuze points.

If there is a need for a P_k for a particular trajectory (for example if you need the P_k for a particular 6-DOF trajectory, or test firing), an approximation may be performed. This approximation is performed by a two-dimensional linear interpolation. One of the four procedures below can be used for each trajectory:

1. The trajectory lies on one of the loci; therefore use the P_k associated with that point.
2. The trajectory lies linearly between two loci; therefore use the standard linear interpolation.
3. The trajectory lies between four loci; therefore use the two-dimensional linear interpolation. (This formula is derived in Appendix C).
4. The trajectory lies on the edge of the database grid. Therefore the P_k values are 0.0 or near 0.0. Use 0.0 for the loci that do not exist and then use procedure 3, above.

Remember that each grid is for a specific dive angle, a specific azimuthal angle, and a specific terminal velocity of the missile. The number of grids needed to cover the range of terminal values that the missile may have, and the granularity that is needed to reduce error, must be determined by prior analysis with the 6-DOF model. For a discussion of the effects of missile velocity, see the formulas in Appendix D. The dive and azimuthal angles are more difficult to understand. The solution lies in a robust design of the warhead and fuze, and the specific geometric configuration of the target. The only way to determine if there is a sensitivity problem with the terminal angles is to run several test cases and from their results, determine the best mix. In order to save time and money, these test cases should be less finely detailed than the actual grid used for final P_k.

As stated earlier, several detonation points may be selected along a trajectory. The purpose of this type of analysis is to help determine the optimal detonation point for a given trajectory. This is a "perfect fuze" study; given the particular characteristics of the proximity sensor being used in the missile system, it may be possible to ensure that the parameters of the proximity sensor are selected to provide near optimal P_k.

A side benefit of perfect fuze analysis is a study of the whole P_k space. This information will give the analyst insight into the entire P_k distribution around the target. This information may be useful in the study of collateral damage to other targets that are in the general vicinity of the targeted threat. An example of this would be a study of the P_k of a threat site attacked using one missile. Generally the individual components of a site must be in close proximity to the targeted threat (as would occur on a ship) for this study to make sense.

PROGRAMS USED IN LETHALITY ANALYSIS

There are three program elements needed to develop a P_k analysis: the proximity sensor program, the P_k program, and the integration program.

Proximity Sensor Program

The proximity sensor program takes the terminal conditions and a mathematical representation of the actual proximity sensor, along with a mathematical model of the surface image of the target, and determines the position where the detonation would occur.**

Currently, the NAWCWPNS Weapons Simulation and Data Analysis Branch is using a derivation of the Ordnance System Analysis for Surface Targets (OSAST) program, originally developed by the late Louis Giegerich and modified by Pierre Pastor.*** The OSAST program sets up the grid of loci with a given dive angle, azimuthal angle, and velocity. Using one of two proximity sensor types, the program then flies straight line trajectories from each locus along the dive angle and azimuthal angle and determines the position where detonation should occur (see Figure 1).

The first proximity sensor type is the optical sensor. The selected parameters for the optical sensor are:

DELAY	time delay (single range gate)
STKANG	"look angle" off the missile nose
RMIN	inner range cutoff
RMAX	maximum detection range
ROT	angle about the missile longitudinal axis at which the fuze is pointed
DISTNW	distance of the warhead from the missile nose
DISTNF	distance of the fuze from the missile nose
IFSTK	number of beams in the optical fuze model

If an object comes into the detection zone of the optical sensor, a detection will be registered unless the object comes between the inner range cutoff and the body of the missile. If an object is inside the inner range gate cutoff (RGC), no light will be reflected back to the sensor; therefore no detections can occur.

*L = number of loci in the ring; p = probability of being in the ring; P_{k_ξ} = probability of kill for locus ξ

$$\sum_{\xi=1}^{L} \frac{P}{L}\left(P_{k_\xi}\right) = \frac{P}{L}\sum_{\xi=1}^{L}\left(P_{k_\xi}\right) = p\frac{\sum_{\xi=1}^{L}\left(P_{k_\xi}\right)}{L}$$

**Some fuzes take actuators of the particular missile into account. This must be modeled to accurately determine the detonation point.

***Documentation on the program may be found in NAWCWPNS TP 8048.

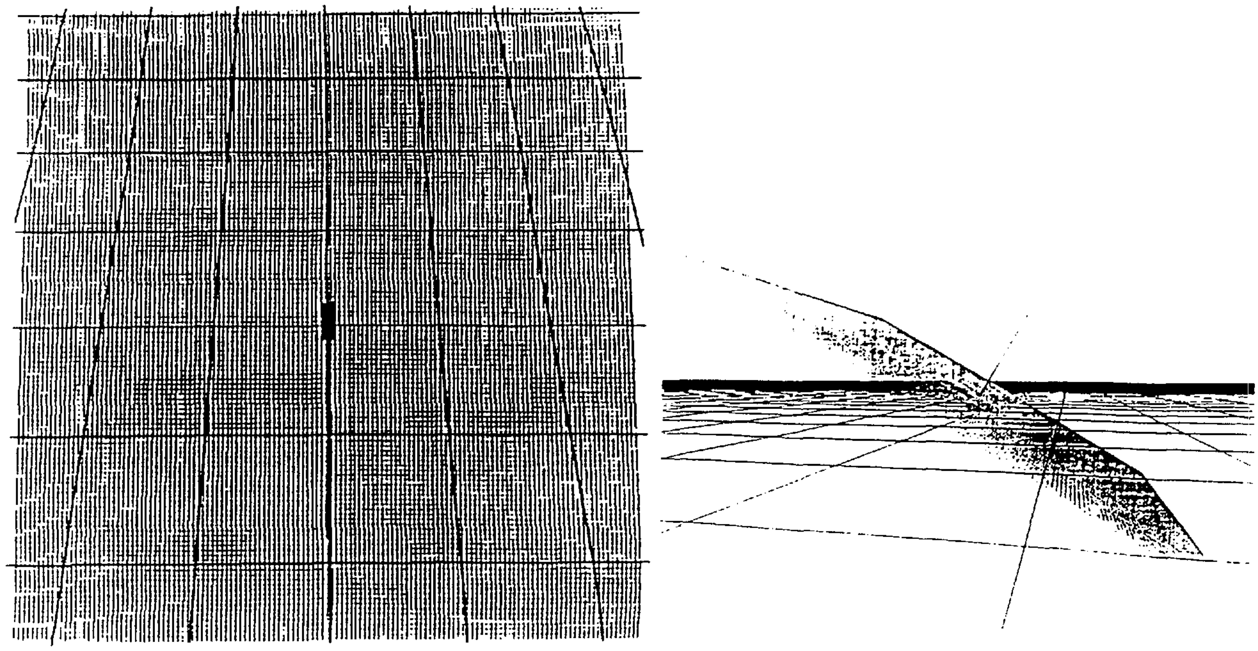


FIGURE 1. Grid of Loci Around a Hypothetical Target.

The second proximity sensor type is the radar frequency sensor. Unlike the standard stick cone sensor model, OSAST has been modified to consider the shape of the detection space. Every radar has a beam pattern where detections may occur. This feature has been considered in the modified OSAST. The inputs to OSAST for the radio frequency proximity sensor are:

XINTIM	integration time
DELAY	time delay (single range gate)
ANTENNA SPREA	360, 180, 90 degrees (about axis)
ALPHA	"look angle" (measured from the missile axis; this is the angle up to the maximum gain region)
RGON	range gate "turn on" in feet
RGC	range gate cutoff
NRGATE	number of range gates
DEL(NRGATE)	delays for range gate NRGATE
AFAMRG(NRGATE+1)	mean range gate cutoff
RGMEAN	mean ground detection range (with the beam pointing downward in the vertical plane)
RTMEAN	mean target detection range (when the target is in the maximum gain region, RTMEAN should equal the RGC for sensitive fuzes or zero for non-target sensitive fuzes)
THETA_3dB	antenna beam width (down to half-power gain; this assumes a gain function that is symmetric about the missile's longitudinal axis)
DISTNW	distance of the warhead from the missile nose
DISTNF	distance of the fuze from the missile nose

Examination of other new fuze technology is currently under way.

Probability of Kill Program

After the detonation location and the terminal conditions are determined, P_k is calculated. Care must be taken when selecting the correct P_k model. P_k models have certain assumptions integrated into their design. One assumption is that the target does not move, an assumption that is made in the P_k program that the NAWCWPNS Weapon Simulation and Data Analysis Branch is using. In our analysis this is not a bad assumption as targetable radars do not move very quickly in relation to the ground. However, if one tried to use this program for ballistic missiles there would be a problem. Ballistic missiles move very quickly, and the velocity vectors of the fragments related to the targets would be incorrect.

Another important element when considering P_k programs is whether the program has the point burst option. A P_k program without the point burst option assumes that the fragments encountering the target have parallel trajectories. This would be true if the detonation of the warhead is sufficiently distant from the target. However, if the target is close to the location of warhead detonation, then this assumption is inadequate to account for the geometry. As fragments enter into frames and vulnerable components, the fragments slow down and are shielded from other components. If a warhead burst is located close to the target, the vulnerable components that it could interact with would be different if the fragments had parallel trajectories. Figure 2 illustrates this point.

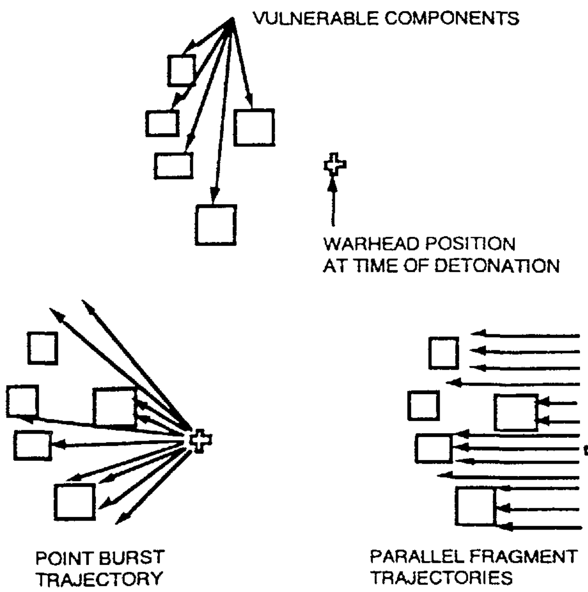


FIGURE 2. Point Burst Versus Parallel Fragment Trajectories.

The effects of both warhead blast and fragmentation must be addressed. It is important to remember that kills due to blast and fragmentation are not necessarily stochastically independent events. Per the *Mathematics Dictionary*, fourth edition, ". . . Two events are independent if the occurrence or nonoccurrence of one of them does not change the occurrence of the other event . . . " (Reference 2). It is dangerous to always assume that $P_k = 1 - \left(1 - P_{k_{Blast}}\right)\left(1 - P_{k_{Frag}}\right)$ It is usually not true. According to James W. Williams, there is a synergistic effect of blast and fragments (Reference 3). To date, the author does not know of any model that simulates this action.

The P_k program that the NAWCWPNS Weapon Simulation and Data Analysis Branch uses is a modification of the General Point Burst Program (GPBP). The original Analyst Manual for GPBP is dated May 1972 (Reference 4). Since that time GPBP has been modified by many individuals, including Robert Collins and the author, both of the Weapon Simulation and Data Analysis Branch. The code was originally written in FORTRAN V on the Univac 1108, but our version is now in FORTRAN 77 on the Silicon Graphics Power Series in the UNIX environment. GPBP has been used by the Weapons Effectiveness Branch (and also by the NAWCWPNS Weapons Systems Analysis Division) for many of the published P_k values in the current Joint Munitions Effectiveness Manuals (JMEMs).

Integration Program

The main purpose of the Integration Program is to calculate the P_k versus CEP using the data derived from the P_k program. The program that the Weapon Simulation and Data Analysis Branch wrote calculates the P_k for points every foot along spokes that are 1 degree apart. The use of spokes ensures that every ring has the same degree of accuracy. The results of the Integration Program are P_k versus CEPs from 1 foot to 40 or 70 feet. In this analysis, a 0-foot CEP contradicts one of our primary assumptions. In Appendix A, we state that $\sigma_1 \neq 0$ and $\sigma_2 \neq 0$. A 0-foot CEP would force $\sigma_1 = 0$ and $\sigma_2 = 0$. The mathematics of the Integration Program are described in the Method of Lethality section of this publication. The Integration Program results are in both tabular and graphical format. The graphical format is beneficial in understanding the interrelationship of the warhead, fuze, missile terminal conditions, and target.

GRAPHICAL DISPLAY AND VISUALIZATION PROGRAMS THAT HELP THE ANALYST UNDERSTAND THE ABOVE DATA

Many graphical programs have been produced to aid the analyst in understanding the interrelationships between the warhead, fuze, terminal conditions, and target. All of the programs described in this paper are written in either C or FORTRAN on Silicon Graphics computers. The graphical programs have increased the productivity of the analyst and have given more insight into the problems of lethality analysis. The graphical programs may be divided into four categories:

1. fragment fly out programs
2. P_k space
3. resulting charts and graphs
4. target production

Each of these are discussed below. Examples are also provided.

Fragment Fly Out Programs

For many years China Lake has had a program that calculates the position of fragments from a warhead at any specific time. In 1990 the graphical capability of the Silicon Graphics computer was used to enhance the program. The contractor, ASI, was employed to animate the fragment fly out program in order to observe the fragment paths and thus obtain a clearer sense of warhead capability. Shomod, the work done by ASI, has enhanced program results.

Shomod is made up of two programs, Frag-Fix and Showmiii. Frag-Fix is a fragment 3-DOF simulation that interacts with the prescribed target. Showmiii takes the results of the Frag-Fix program and shows them graphically on a monitor.

The Shomod package enables the analyst to watch fragment fly out and thereby observe warhead problem areas such as dead zones (areas where no fragments appear, such as around the velocity vector of the missile). The ability to watch fragments fly out from the missile in given trajectories affords the analyst insight into specific problems. Shomod has also been used to check target models and warhead models for completeness and accuracy.

Probability Of Kill Space Programs

The output of the P_k program is thousands of lines long and quite complicated. The P_k space program was written to graphically see the output from GPBP.

The P_k space program was envisioned by Louis Giegerich and implemented by Rama Gheris. However, there is no published documentation. The concept of this program is to place a marker in three-dimensional space where the warhead will detonate and then color the marker to illustrate the P_k that the warhead would achieve at that location.

This program can concurrently overlay several files to illustrate the difference between warheads and/or fuze systems. Detailed examination may be achieved by looking at the data in slices (i.e., looking at the fuze/P_k space by cross range data or by down range data). An extremely helpful aspect of this program takes all the fuze space data from the formulation of the "perfect fuze" analysis and compares these data to the current fuze space. This has helped in the development of parameters needed by fuze designers.

When seemingly strange results occur in the lethality analysis, we are able to call upon the above package to help the analyst understand the results, rather than to simply disregard the data and try again. When the data are bad, this program has been able to locate the problem with the models. Often the data are good and new insight into the interrelationship is developed quickly.

Resulting Charts and Graphs

The output of the integration program is placed into a file for archiving. Robert Collins, NAWCWPNS China Lake, has further developed the programs the author wrote that develop charts and graphs. His program takes these columns of numbers (the program's output) and integrates this output into either line or bar graphs. This allows us to see the falloff of P with an increase of CEP. We can also look at several fuze/warhead/trajectory/target systems at one time. This ability not only allows us to compare multiple systems but also allows us to optimize a given system by changing particular parameters.

TARGET PRODUCTION

A program is currently being developed by Robert Collins with the help of the NAWCWPNS Weapons Effectiveness Branch. This graphical aided program will produce target models. When completed, target models will be developed and debugged faster because the models will be built with interactive graphics.

THE FUTURE

There are several areas of concern that the Weapons Simulation and Data Analysis Branch has with regard to lethality analysis. They are:

1. Effects of tungsten, titanium, and other materials on penetration, shattering, and high energy effects
2. Effects of target material, including steel and aluminum
3. Effects of encounter geometry, including velocity, angles of obliquity, and fragment shapes
4. Effects of reactive armor
5. Effects of non-fragment penetrations such as high energy plasma, particle beam, and electromagnetic pulse
6. Effects of vegetation and different mediums
7. Multiple fragment effects (Gurney effects)
8. Multiple target plate effects
9. Effects of the "new" explosives
10. Effects of different boosters
11. Effects of different booster locations
12. Effects of different warhead shapes
13. Effects of different case materials and thicknesses
14. Calculating the shielding effect of the vehicle that contains the warhead
15. Effects of directed warheads
16. Effects of pure blast, penetrations, or exotics

The main question is how to model them in both the area of fuzing and in the area of P_k.

This area of analysis has never been more exciting or more rewarding. Expanded research and modeling must be accomplished so that when questions arise, we are in a position to answer them.

REFERENCES

1. Edwin L. Crow, Frances A. Davis, and Margaret W. Maxfield. *Statistics Manual*, New York, Dover Press, 1960, p. 29.
2. *Mathematics Dictionary*, 4th ed. James Glenn, ed. New York, Van Nostrand Reinhold Co., Inc., 1976.
3. Naval Weapons Center. *Near Field Effects Warhead*, by James W. Williams. China Lake, Calif., NWC, July 1980. (Publication UNCLASSIFIED.)
4. _____. *General Point Burst Program (GPBP) Volume II. Analyst Manual*, by Armament Systems, Inc., and NWC Propulsion Development Dept. China Lake, Calif., NWC, April 1972. (Technical Note 4565-5-72 Vol. II, publication UNCLASSIFIED.)

Appendix A. Derivation of a Probability of a Miss Distance or Less Given the Standard Deviation

Given a bivariate normal distribution:

$$f(y_1,y_2) = \frac{e^{-\frac{Q}{2}}}{2\pi\sigma_1\sigma_2\sqrt{1-\rho}}$$

for $-\infty < y_1 < \infty$ and $-\infty < y_2 < \infty$ where

$$Q = \frac{1}{1-\rho^2}\left[\frac{(y_1-\mu_1)^2}{\sigma_1^2} - 2\rho\frac{(y_1-\mu_1)(y_2-\mu_2)}{\sigma_1\sigma_2} + \frac{(y_2-\mu_2)^2}{\sigma_2^2}\right]$$

Now if y_1 and y_2 are independent random variables then

$$E(Y_1Y_2) = E(Y_1)E(Y_2) = \mu_1\mu_2$$

Therefore

$$\begin{aligned}\rho\sigma_1\sigma_2 &= Cov(Y_1Y_2)\\ &= E[(Y_1-\mu_1)(Y_2-\mu_2)]\\ &= E(Y_1Y_2) - \mu_1\mu_2\\ &= \mu_1\mu_2 - \mu_1\mu_2\\ &= 0\end{aligned}$$

Therefore $\rho = 0$ since $\sigma_1 \neq 0$ and $\sigma_2 \neq 0$

Then if $\sigma_1 = \sigma_2$ and $\mu_1 = \mu_2 = 0$

Then

$$f(y_1,y_2) = \frac{e^{-\frac{Q}{2}}}{2\pi\sigma^2}$$

$$Q = \frac{y_1^2}{\sigma^2} + \frac{y_2^2}{\sigma^2} = \frac{y_1^2 + y_2^2}{\sigma^2}$$

or

$$f(y_1,y_2) = \frac{e^{-\frac{y_1^2+y_2^2}{2\sigma^2}}}{2\pi\sigma^2}$$

Now if we make the substitution of y = r cos Θ and y = r sin Θ then we have

$$y_1^2 + y_2^2 = (r\cos\Theta)^2 + (r\sin\Theta)^2$$
$$= r^2\cos^2\Theta + r^2\sin^2\Theta$$
$$= r^2(\cos^2\Theta + \sin^2\Theta)$$
$$= r^2$$

Therefore we have

$$r = \sqrt{y_1^2 + y_2^2}$$

and

$$\tan\Theta = \frac{y_2}{y_1}$$

The Jacobian of this transformation is

$$\begin{vmatrix} \frac{\partial y_1}{\partial r} & \frac{\partial y_1}{\partial\Theta} \\ \frac{\partial y_2}{\partial r} & \frac{\partial y_2}{\partial\Theta} \end{vmatrix} = \begin{vmatrix} \cos\Theta & -r\sin\Theta \\ \sin\Theta & r\cos\Theta \end{vmatrix}$$
$$= r\cos^2\Theta + r\sin^2\Theta$$
$$= r\left(\cos^2\Theta + \sin^2\Theta\right)$$
$$= r$$

Now by

$$\int_S h(Q)dS = \int_R h(F(P))\left|\frac{\partial(f,g)}{\partial(u,v)}\right|dA$$

we have

$$\int_R f(r,\Theta)\ r\ dA$$

Now understanding that dA = dr dΘ we have

$$\int_0^{2\pi}\int_0^{x}\frac{e^{-\frac{r^2}{2\sigma^2}}}{2\pi\sigma^2}r\ dr\ d\Theta$$

Now let

$$u = r^2$$
$$du = 2\ r\ dr$$

Therefore

$$\int_0^{2\pi}\int_0^{x^2}\frac{1}{2}\frac{e^{-\frac{u}{2\sigma^2}}}{2\pi\sigma^2}du\ d\Theta$$

$$= \int_0^{2\pi}\frac{1}{2\pi}e^{-\frac{u}{2\sigma^2}}d\Theta$$

$$= -e^{-\frac{u}{2\sigma^2}}\Big|_0^{x^2}$$

$$= 1 - e^{-\frac{x^2}{2\sigma^2}}$$

Appendix B. Derivation of the Relationship of CEP and the Standard Deviation in a Bivariate Normal Distribution

Given a bivariate normal distribution, the probability that a realization of the distribution is within x distance of the mean is given by

$$1 - e^{-\frac{x^2}{2\sigma^2}}$$

Then the probability of the realization of the distribution is ≥ x

$$e^{-\frac{x^2}{2\sigma^2}}$$

How CEP is related to σ * can be determined by the following manner

$$1 - e^{-\frac{x^2}{2\sigma^2}} = e^{-\frac{x^2}{2\sigma^2}} \quad \text{(Here x represents the CEP.)}$$

$$1 = e^{-\frac{x^2}{2\sigma^2}} + e^{-\frac{x^2}{2\sigma^2}}$$

$$1 = 2e^{-\frac{x^2}{2\sigma^2}}$$

$$\log_e(1) = \log_e\left(2e^{-\frac{x^2}{2\sigma^2}}\right)$$

$$0 = \log_e(2) - \frac{x^2}{2\sigma^2}\log_e(e)$$

*The bivariate normal probability distribution states that 50% of the realizations of a probability distribution are within the radius of a circle and thus 50% of the realizations of a probability distribution are outside the circle.

$$0 = \log_e(2) - \frac{x^2}{2\sigma^2}$$

$$\frac{x^2}{2\sigma^2} = \log_e(2)$$

$$x^2 = 2\sigma^2 \log_e(2)$$

$$x^2 = \sigma^2 2\log_e(2)$$

$$x = \sigma\sqrt{2\log_e(2)}$$

Appendix C. Derivation of Two-Dimensional Linear Interpolation

Let $P_1 = (x_1,y_1)$, $P_2 = (x_1,y_2)$, $P_3 = (x_2,y_1)$, and $P_4 = (x_2,y_2)$ be loci and let $P_5 = (x_3,y_3)$ be a point that lies in the interior of the quadrilateral formed by points P_1, P_2, P_3, and P_4. If there is a continuous function f that exists for all points bounded by the quadrilateral and the function forms a plane, then $f(P_5)$ may be found by the following:

First select two new points $P'_1 = (x_1,y_3)$ and $P'_2 = (x_2,y_3)$. Now find $f(P'_1)$ and $f(P'_2)$. $f(P'_1)$ and $f(P'_2)$ may be found by use of the standard linear interpolation.

For P'_1

$$\frac{f(P'_1) - f(P_1)}{f(P_2) - f(P_1)} = \frac{y_3 - y_1}{y_2 - y_1}$$

$$[y_3 - y_1][f(P_2) - f(P_1)] = [y_2 - y_1][f(P'_1) - f(P_1)]$$

$$\frac{[y_3 - y_1][f(P_2) - f(P_1)]}{[y_2 - y_1]} = f(P'_1) - f(P_1)$$

$$\frac{[y_3 - y_1][f(P_2) - f(P_1)]}{[y_2 - y_1]} + f(P_1) = f(P'_1)$$

Likewise for P'_2

$$\frac{f(P'_2) - f(P_3)}{f(P_4) - f(P_3)} = \frac{y_3 - y_1}{y_2 - y_1}$$

$$[y_3 - y_1][f(P_4) - f(P_3)] = [y_2 - y_1][f(P'_2) - f(P_3)]$$

$$\frac{[y_3 - y_1][f(P_4) - f(P_3)]}{[y_2 - y_1]} = f(P'_2) - f(P_3)$$

$$\frac{[y_3 - y_1][f(P_4) - f(P_3)]}{[y_2 - y_1]} + f(P_3) = f(P'_2)$$

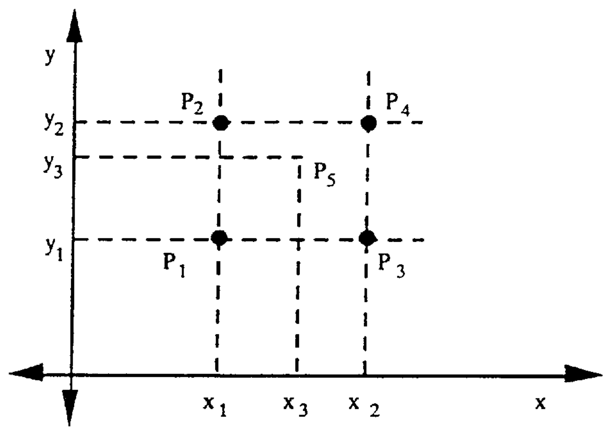
Now we have $P'_1 = (x_1,y_3)$, $P'_2 = (x_2,y_3)$, and $P_5 = (x_3,y_3)$, which are colinear. Therefore we can again use the standard linear interpolation:

$$\frac{f(P_5) - f(P'_1)}{f(P'_2) - f(P'_1)} = \frac{x_3 - x_1}{x_2 - x_1}$$

$$[x_3 - x_1][f(P'_2) - f(P'_1)] = [x_2 - x_1][f(P_5) - f(P'_1)]$$

$$\frac{[x_3 - x_1][f(P'_2) - f(P'_1)]}{[x_2 - x_1]} = f(P_5) - f(P'_1)$$

$$\frac{[x_3 - x_1][f(P'_2) - f(P'_1)]}{[x_2 - x_1]} + f(P'_1) = f(P_5)$$



Appendix D. The Effects of Missile Velocity on Fragment Fly Out

The dynamic shift of fragment vector angles can be calculated given the following

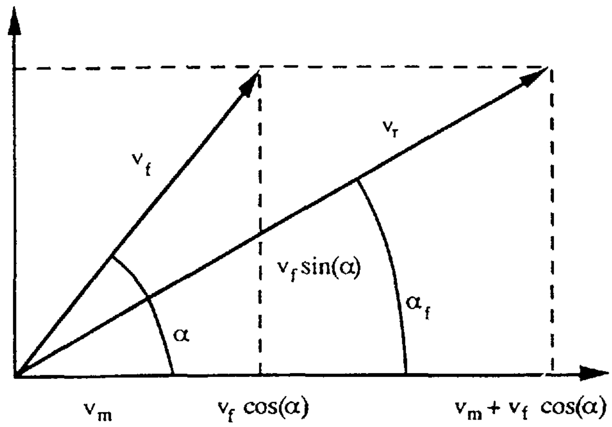
v_m = missile velocity with respect to the ground
v_f = fragment velocity with respect to the missile
v_r = fragment velocity with respect to the ground
α = fragment angle to the missile with respect to the missile
α_r = fragment angle to missile with respect to the ground

where

$$v_r = \sqrt{(\sin(\alpha)\, v_f)^2 + (v_m + \cos(\alpha)\, v_f)^2}$$

and

$$\alpha_r = \tan^{-1}\left(\frac{v_f \sin(\alpha)}{v_m + v_f \cos(\alpha)}\right)$$



Let us use an example:

$$v_{m_1} = 800.0 \text{ and } v_{m_2} = 1000.0 \text{ feet/sec}$$

Let us also state that $v_f = 5000.0$ feet/sec

Original angle α, degrees	Resultant angle Using $V_m = 1000$ α_r, degrees	Using $V_m = 800$ α_r, degrees	Difference $\delta\alpha_r$, degrees
10	8	9	0.287
20	17	17	0.572
30	25	26	0.853
40	34	35	1.126
50	42	44	1.389
60	51	53	1.637
70	60	62	1.864
80	69	71	2.061
90	79	81	2.22
100	88	91	2.327
110	99	101	2.368
120	109	111	2.328
130	120	122	2.192
140	131	133	1.947
150	143	145	1.591
160	155	156	1.13
170	168	168	0.587
180	180	180	

In this case the greatest difference in the resultant angles is 2.368 degrees. Also in this case, errors in the fuze model and the P_k model would account for more errors than could be accounted for by a change in velocity. If there is a problem, another set of grids with another missile terminal velocity can be generated.

Again if we use the example from above we receive:

Original angle α, degrees	Resultant angle Using $V_m = 1000$ v_r, feet/sec	Using $V_m = 800$ v_r, feet/sec	Difference $\delta\alpha_r$, feet/sec
	6000	5800	-200.
10	5987	5790	-197.813
20	5950	5758	-191.273
30	5887	5707	-180.44
40	5802	5636	-165.42
50	5695	5548	-146.368
60	5568	5444	-123.501
70	5424	5327	-97.111
80	5267	5199	-67.584
90	5099	5064	-35.424
100	4926	4925	-1.29
110	4752	4786	33.975
120	4583	4652	69.306
130	4424	4527	103.399
140	4282	4417	134.728
150	4164	4326	161.611
160	4075	4257	182.361
170	4019	4214	195.499
180	4000	4200	200.

Again in this case the difference does not warrant a separate grid. The only problem that could be encountered is if the P_k program that is being used has a lookup table with a cutoff between two values. For example, using the fragment size: if the velocity is 5700 or above, the P_k is 0.75. But if the velocity is below 5700, the P_k is 0.42. In this case we would need a new grid.

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EW technologies	EW testing, verification and validation

14. Abstract

Electronic Warfare (EW) has emerged as a critical driving force in modern warfare. New generations of weapon systems directly impact EW requirements and strategies.

Modern combat aircraft are faced with a drastic change of a possible threat scenario consisting of a mix of Western and Eastern weapon systems. The deployment of advanced pulse doppler radar systems in A/A and G/A application augmented by extensive electro-optic capabilities, directed energy weapons (laser or particle beam), electromagnetic/shockwave weapons requires a detailed reassessment of NATO EW processes.

The complexity and diversity of future threat scenarios necessitate changes in NATO EW system concepts, and an update of existing equipment including modifications of tactics and combinations of EW resources to improve survivability.

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