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

AGARD CONFERENCE PROCEEDINGS NO. 557

Tactical Aerospace C³I in Coming Years

(Commandes, pilotage, communications, renseignements tactiques aérospatiaux dans les prochaines années)

Papers presented at the Mission Systems Panel 3rd Symposium held in Lisbon, Portugal from 15th May to 18th May 1995.

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Tactical Aerospace C^{3}I in Coming Years

(AGARD CP-557)

Executive Summary

The conference brought together representatives from MODs, manufacturers and academics from most of the Alliance countries.

It demonstrated that major C3I developments for air forces are underway, particularly in the United States (Theatre Battle Management), in France (SCCOA) and at NATO (ACCS). These C3I systems combine all the real time (surveillance, air mission control), and deferred functions (force planning and management) at a very high level of complexity.

In effect, they constitute "system systems" and as such, justify the development of suitable methodologies. The problem is to organise, manage and control data flows between complex elements; tools are being developed around the programmes concerned. Quite the opposite to the top-down approach, the way in which commercially available hardware and software is integrated into C3I has been the subject of much discussion. Although interesting from the cost point of view, the use of off-the-shelf components presents a number of trade-off problems with regard to conformity to system specifications and invariably leads to a cost-efficiency analysis.

From the technical point of view, the first applications of the real time fusion of complex data were presented: multiradar tracking, fusion of identification data, generation of situational displays with multiple aircraft and targets. A variety of methods were successfully applied.

Finally, future developments will probably concentrate on:

— the extensive use of digital data links, with a trend towards very wide bandwidths

— the real-time application of high resolution radar and optical sensors for observation of future theatres of operations

— the introduction of decision making aids for ops. planning and air mission preparation

— a general trend towards real-time operations control minute by minute or even by second, in a joint or combined forces context

Commandes, pilotage, communications, renseignements, tactiques aérospatiaux dans les prochaines années

(AGARD CP-557)

Synthèse

Le colloque a réuni des représentants des Ministères de la Défense, des industriels, et des universités de la plupart des pays de l'Alliance.

Il a révélé que des développements majeurs de C3I pour les forces aériennes sont en cours, notamment aux Etats-Unis (Theater Battle Management), en France (SCCOA) et à l'OTAN (ACCS). Ces C3I fédèrent toutes les fonctions temps réel (surveillance, conduite des missions aériennes) et temps différé (planification, gestion des forces) à un niveau de complexité très élevé.

Ils constituent en fait des Systèmes de Systèmes, et justifient à ce titre le développement de méthodologies adaptées. Le problème consiste à organiser, maîtriser et gérer les flux d'information entre des ensembles complexes; des outils sont en cours de développement autour des programmes concernés.

A l'opposé de l'approche top-down, la manière d'intégrer dans les C3I des produits hardware et software du commerce a été largement évoquée. Intéressante du point de vue des coûts, l'utilisation des COTS pose des problèmes de compromis dans le respect des spécifications du système et conduit en permanence à une analyse de coût-efficacité.

D'un point de vue technique, les premières applications de fusion en temps réel d'informations complexes ont été présentées : poursuite multiradars, fusion de données d'identification, génération de situations aériennes composites. Différentes méthodes sont appliquées avec succès.

Enfin, les évolutions dans l'avenir semblent se concentrer sur

— l'utilisation extensive de liaisons de données numériques, avec une tendance vers de très larges bandes passantes,

— la mise en œuvre en temps réel de capteurs optique et radar à haute résolution pour l'observation du théâtre d'opérations,

— l'introduction d'aides à la décision pour la planification des opérations et la préparation des missions aériennes,

— et d'une manière générale, vers la conduite des opérations en temps réel à l'échelle des minutes, voire des secondes, dans un contexte interarmées et interalliés.

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Theme

C³I Systems are defined as an integrated system of doctrine, procedures, organization, personnel, equipment, facilities, and communications to provide authorities at all levels with timely and accurate data to plan, direct, coordinate and to control their operations and crisis mobilization and combat. The present C³I systems with all their imperfections and deficiencies, have been developed based on the confrontation of massive forces. The recent events in the Persian Gulf have shown that the existing systems have certain deficiencies. As progress is made with Arms Control and Conventional Force Reduction in Europe, the defense and safety of Europe will have to depend more and more on technical superiority and sustainability. It appears that successful execution of wars and conflicts in the future will require the latest systems for remote sensing, aerial/space observation, data transfer, data fusion and dissemination, interoperability between systems, and Command and Control capabilities. In other words, a decisive advantage will be gained by that side who can deploy and manoeuver its smaller and flexible forces by employing systems to provide early warning and intelligence and who can rapidly process and fuse the information and deploy it to the correct Command and Control structures.

The topics covered addressed the new requirements for C³I structures in the coming decades and the application of the most modern techniques and technologies such as AI for rapidly and reliably collecting, processing and fusing information and making available to the Commander decision options. Some of the topics of interest are the following:

— Threat perception in the coming decades (uncertainty in aims, scope, time and location).
— Assessment of the capabilities and potential development of present systems.
— Advanced situation assessment (sensor data fusion for intelligence and generation of air picture, including identification of friend and foe).
— Decision aids for planning, tasking and execution.
— Communication techniques and network (MIDS, ...).
— Standards, Open System Architecture (OSA), man-machine interfaces.

Thème

Les systèmes C³I peuvent être définis comme des systèmes intégrés de doctrine, de procédures, d'organisation, de personnel, d'équipements, d'installations et de communications destinés à fournir aux autorités à tous les niveaux, des données précises et pertinentes, permettant la planification, la conduite, la coordination et le contrôle des opérations, ainsi que la mobilisation en situation de crise et de combat.

Les systèmes C³I actuels, avec leurs imperfections et défauts ont été développés en vue de la confrontation de forces massives. Les événements récents dans le Golfe Persique ont démontré que les systèmes actuels ont certaines déficiences. Avec la maîtrise des armements et la réduction des forces conventionnelles en Europe, la défense et la sécurité de l'Europe dépendront de plus en plus de leur supériorité technique et de leur capacité de soutien. Il semblerait que la conduite des guerres et des conflits à l'avenir exigera la mise en œuvre des derniers systèmes de télédétection, d'observation aérienne/spatiale, de transfert des données, de fusionnement et de diffusion des données, d'interopérabilité entre systèmes et de commandement et contrôle.

Autrement dit, un avantage décisif est à prendre par le camp qui saura déployer et manœuvrer des forces réduites et plus flexibles à l'aide de systèmes d'alerte avancée et de renseignement, et qui sera en mesure de traiter et de fusionner les données rapidement pour les transmettre aux structures de commandement et de contrôle appropriées.

Les sujets présentés couvriront les nouveaux besoins en structures C³I pour les décennies à venir, ainsi que l'application des dernières techniques et technologies telles que l'IA pour la collecte, le traitement et le fusionnement rapides et fiables des informations et la mise à disposition d'options décisionnelles pour le commandant.

Parmi les sujets traités on distingue:

— la perception de la menace dans les décennies à venir (incertitudes concernant les objectifs opérationnels et leur localisation spatio-temporelle).
— l'évaluation des capacités et l'évolution potentielle des systèmes actuels.
— l'évaluation avancée de la situation (fusionnement des données senseur pour le renseignement et l'élaboration de la représentation de la situation aérienne, y compris l'IFF).
— les aides à la décision pour la planification, la répartition des tâches et l'exécution.
— les techniques et les réseaux de communication (MIDS ...)
— les normes, l'architecture des systèmes ouverts (OSA), les interfaces homme-machine.

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TECHNICAL EVALUATION REPORT

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1) Overview

The Agard Mission Systems Panel 3rd **Symposium on Tactical Aerospace C3I in coming years** was held in Lisbon , Portugal from 15 to 18 may , 1995 .The meeting was chaired by Mr Jacques Cymbalista from France with Mr Bruno Mazetti from Italy as deputy . 192 representatives from 14 nations attended the symposium . The audience was composed of representatives from the military community (MOD's and Forces) , from government agencies , from university and from industry , by far the most numerous .
The Symposium occurred at a time when the geopolitical context , namely the increase of crisis situation since the end of the Cold War , impulses many C3I activities in the Government agencies and in the Industry .

In the first keynote address , Pr. Fernando Carvalho Rodrigues from Portugal addressed the role of small satellites as support elements to C3I systems .
As a matter of fact , the development of Low Earth Orbit applications , using sophisticated ,though light satellites tightly coordinated in a C3I network will be a major trend in the next years : the civilian programs such as Globalstar or Iridium , for handheld communication will be a key to integrated battlefied concepts such as "C4I for the Warrior " (it may be reminded that Agard sponsored a conference on Tacsats for Surveillance , Verification and C3I in 1992)

The spectrum and the coverage of the presentations were very large and most of the key questions , issues , and achievements relevant to the Tactical Aerospace C3I were addressed by the authors .
As far as the *coming years* are concerned , the meeting demonstrated that the Nato community is working within the frame of two overlapping schedules :

-**year 2000** or so is a first milestone to provide the Nato Air Forces with an integrated set of systems , to perform *surveillance* and *identification* within the airspace , to *manage the resources* , and to *plan , prepare* and *control* the missions . Major programs are going on or under preparation :

- the NATO Air Command and Control System (ACCS) was briefed by the NACMA General Manager ; year 2001 will see the completion of a first level of operational capability for the system ;

-the french Air Force and the French MOD described the SCCOA (Système de Commandement et de Conduite des Operations Aériennes) , the development of which is underway since 1992 , with incremental delivery of equipment and integrated C2 centers from 1996 to beyond year 2000 ;

-the USA presented the effort underway for the development of TBM (Theater Battle Management) , a follow-on to CTAPS (Contingency Tactical Air Force Planning System) .

A common feature of these systems is that they are actually *Systems of Systems* , federating high level functions and equipment in a comprehensive architecture .
One key reason is the development of **combined , joint** operations , a major lesson from Desert Storm and from the geopolitical situation that follows the collapse of the Warsaw Pact .
The need for Combined Operation Centers (CAOCs) derives from the combination of all defensive , offensive and support operations , under a single theater commander who plans and controls the missions in the airspace ; his authority and responsibility , not only on national Air Force elements but on

multinational Air Forces , Navies and Armies assets drives requirements for communication , shared procedures and for time phasing ; hence an intricated architecture mixing surveillance , airspace management , air traffic control , force management , air mission control and C2 resources allocation. Intelligence of course fuels the process .

A second major trend is the push towards *mobile* configuration , rather than (or in parallel with) a fixed architecture .
The ACCS has been switching from a fixed , backbone architecture in Central Europe (designed during the Cold War era) , to a *Deployable ACCS Component* , more flexible and able to conduct "out - of - area" operations. The french SCCOA system is made of both a fixed and an air transportable architecture , and the US TBM is basically dedicated to unpredictable theater operations , and therefore flexible .
Interoperability is the key word for systems that shall be able to share and process information , often in contingency operations , i.e under circumstances that were not preplanned . It is therefore mandatory that Nato nations develop systems that are basically interoperable in order to allow connectivity ; but this is not enough , since interoperability requires *common doctrines* and *common procedures* .

The use of commercial equipment (hardware or software) - COTS (for Commercial-Off-The-Shelf) should help interoperability , since the commercial subsets focus towards single (or at least compatible) standards . Generally speaking , the dramatic increase in performance level , along with the collapse of the cost , of commercial hardware and software is driving the burst of the information systems.

-years 2005 to 2010 might be the second milestone for aerospace C3I : the issue would be then to take advantage of all and any assets on the theater in a distributed architecture .

A comprehensive overview from the Mitre Corporation described the *infosphere* , a complex combination of all pieces of information available on the theater , from the fusion of all sensors data , let them be space-, air- or ground-based .
In the same time , the weapons are tightly embedded in a loop of information , action and assessment . As the capability and accuracy of the weapons increase , the need for more sophisticated information (namely images) and for shorter processing and transmission delay becomes more stressing : Information highways are then mandatory ; another presentation demonstrated the capabilities for high data rate transmission using the Asynchronous Transfer Mode .

On the other hand , the intrication of capturing the proper near real time accurate information to feed the decision process and the weapon systems was addressed in three presentations : one demonstrates the availability of high grade real time ground surveillance information using airborne sensors (the Horizon helicopter-borne radar system); another depicts the stategies that are needed to manage optimally multiple spacebased intelligence sensors ; the third describes real time algorithms for updating and planning in real time search patterns for precision terminally guided missiles .

The issues that are opened by this trend to **cooperative engagement** of **highly accurate** weapons fed in **real time** by **large size** pieces of information are numerous . We propose in the recommendations for future efforts that some of them be addressed in the prospects of the Mission Systems Panel .

A summary of the main discussions and conclusion will now be presented according to the breakdown of the sessions of the symposium : (1) Architecture , requirements and trends , (2) Situation assessment , (3) Decision aids for planning , tasking and execution , and (4) Techniques and technologies .

2) Architecture , requirements and trends

The presentations of major developments going on in Nato nations or under the auspices of the dedicated Nato Agency , the NACMA , addressed the issues that underly the new concept of a total Aerospace C3I design :

-the size and criticalness of the information to be processed : the french Air Force reminded that as many as **10000** aircraft (civilian and military) use its national airspace;Europe is actually a choke point , and the military C3 has

to interoperate with the civilian organisation , at least in peace and crisis time , i.e the driving situation after the cold war era .

-the design of systems federating extremely complex subsystems that must interoperate. The notion of *system of systems* was opened , along with the tools it requests .
The specification of a system of system must be accurate enough to make sure that it will fulfill the operational requirements , but flexible enough to let freedom to the subsystems developpers .
MITRE presented methodologies to derive the requirements : a top-down , layered roadmap to identify the relationships and data exchanges between the players, and relying on functional analysis , data management and integrated systems engineering environment models . Flexibility is critical to match new situations ; "what if ?" is a question at the hub of the process .
System of systems deal mainly with the interoperability issue , i.e with the ability to make subsets work together.This requires a common will to share the doctrines , the procedures and the data exchanges ; it is therefore as much a political issue within the organizations , as a technical issue . It was pointed out that the US Air Force has set up a Forum of Principals (i.e an executive panel) in charge of resolving the issues . Similar procedures are implemented in other organizations .

Another critical trend is the growing use of commercial products (COTS) . The push from low cost and high performance level is obvious ; but military systems must fulfill specific requirements (basically environment , security , maintenability ...) that are not necesserily requested for commercial products.

Clearly , there is a gap in the methodology , to drive the trade- offs between two trends :

-design and select according to a top down approach , that may reject COTS that do not prove their ability to fully fulfill the requirements (or spend money to demonstrate the qualification of the COTS to the system requirements)

-make extensive use of COTS , betting that they are not too far from the goals , and solve the potential issues as they rise . The initial cost is obviously much lower but critical issues may emerge on the field .

Several exemples where given , for hardware and for software . No actual recognized methodology is implemented :

- As far as hardware is concerned , good sense is driving and examples were shown of systems developed in very short timeframes (a few months) that proved to work very well , using adapted environment devices .

-Integrating commercial software reqires tools ; none seems to be definitely agreed ; CORBA was presented as *promising but immature .*

A (so far) good conclusion was proposed : due to the availability of COTS , *"the system requirements should be defined in a broader , less rigid fashion;they should be examined and reviewed , but the existence of commercial technology should never be used to cause the capitulation of valid requirements"*

Nevertheless , the very large C3I systems needed for aerospace purposes have generated a need for a new methodology , one step above the classical system engineering process . They manage more information from more sources and with more men in the loop than current systems ; interoperability in changing environments call for flexibility whereas they are usually embedding already existing systems or components that are **not** flexible .
Therefore , methods and tools shall be developped to help the derivation of the right level of requirements at **system of system** level , mainly : exchange flows , interfaces , common procedures and standards , and *ilities* .

3)Situation Assessment

The assessment of the situation requires the generation of an Air Picture from the various sensors (active or passive) and of a Ground and Maritime Picture ; as mentioned earlier , the systems currently under development till year 2000 deal merely with the former , as much work is underway to provide the forces with the latter between years 2000 and 2010.

The Air Picture is derived from the data generated by various radars and passive (ESM) sensors . The main issue is the data fusion from these sources to merge information and enhance the quality of the

Recognized Air Picture (RAP) under any circumstances (saturation , jamming , maneuver of the targets ...). The RAP encompasses detection , track generation and identification .
Several presentations were dedicated to multisensor data fusion for non cooperative targets(i.e the fusion of detection information). It shows that algorithms have been derived and work , based upon the Bayesian theory (multiradar tracking is fielded in the current versions of the french STRIDA system and has been proven and validated) .
Other algorithms based on Fuzzy Logics and the Theory of Evidence have been presented for application to the target recognition problem ; their features may apply according to the nature of the a priori knowledge of the targets ; it seems however that the Bayesian algorithms are still the most commonly used .

The use of passive sensors needs powerful algorithms to derive range information and continuous track data . Norway presented an enhancement of the RAP generation using this method that seems promising .

The second function of the air picture generation is the identification process . The principles and the current applications of the NIS-IDCP concept were briefed in several papers . Still using bayesian estimates , the fusion of several sources was described as feasible and working well . Examples , namely from the french companies , demonstrated that fusion of identification is already implemented not only at Air Force level but also between Air and Army forces in an Air Land Operations environment .

Target recognition using range resolution (i.e wide band signals) , and based on the target shape , was proposed . The question then is which air defense radar (except for SAM engagement radars) could be available to perform this feature against aircraft , and when.
The range (and range rate) resolution is indeed a key to discrimination techniques , a challenge to Extended Air Defense (i.e defense against theater ballistic missiles , for which debris and decoys hinder significantly the engagement process) . But this topic was not addresed during the symposium .

The generation of low altitude RAP , the enhancements to the AWACS , the use of passive or active IR information was not addressed either .

4) Decision Aids for Planning , Tasking and Execution

The planning and tasking functions (that are non real time operations) are the hart of the aerospace C3I systems under development .

The examples briefed show that large software for mission planning , tasking and preparation are being developed . They are implemented on more and more mobile equipment for operations far from the mainland .
Ruggedized equipment seems to be set up , starting from commercial standard PCs or workstations . The experience demonstrates that it may work provided some caution is taken to filter out the environment constraints .
As far as software is concerned , one key element is the geographical databases . It was recalled that there is no actual NATO standard for the databases , but only exchange standards . Open architecture make extensive use of commercial software components . Security is one issue , especially for object oriented databases . there is some contradiction between interoperability and security ; it shall be managed through veto-type procedures , but security clearly downgrades interoperability .
Discretionary and mandatory access control were reviewed , and it was pointed out that the available commercial systems do not comply to levels of security beyond B1 of the Orange Book . It opens a field to additional developments taking more care of security whereas performance should not be degraded and access through all languages (C , C++ , O2C and OQL) should be possible .

Tools were presented to help the commander's work on the field , such as radar deployement organization , and meteo data integration : more and more functions are part of the optimization and decision making process in the currently developped systems .
Looking to the near future , still more advanced concepts were presented in a US paper for adaptive strike planning , i.e updating en route a strike force of precision guided missiles to optimize its search path . This process will become mandatory as the action loop is shortened down to minutes (instead of days or even hours) , including fusion of surveillance and intelligence data , mission planning and preparation , and mission execution to kill mobile targets for example .

5) Techniques and Technologies

This section addressed actually new technologies that will impact the implementation of the future C3I systems .
Intelligence is probably the area where major achievements are needed , since it feeds the process of action on the theater . Hence the need for accurate , flexible sensors providing excellent near real time information .

Trade-offs for radar satellite imaging using SAR radars were presented . Resolutions down to 1 meter for a 20 km wide image was claimed , with an average access time to the target of 10 to 36 hours , using two satellites in low earth orbit .
A strategy to manage the planning of space based observation assets (optical , radar or ESM) was proposed by Aerospatiale ; the challenge is to provide as much information of a given area in as near real time as possible .
It relies on a comprehensive analysis of the mission reqirements and of the features of the systems involved in the process . Optimum matching of the capabilities of the set of sensors with respect of the mission goals is determined .

An helicopter borne MTI radar system for battlefield observation , Horizon , was briefed by Eurocopter . It allows obsevation and location of targets moving at more than 6 km/h at a distance of 150km . It was used during Desert Storm operations and allowed Apache helicopters to strike Iraqi vehicles .

Fast computing techniques were demonstrated by Portugal , who built a parallel architecture machine based on Multiple Instruction Stream/multiple Data Stream . 1.15 Giga events per second can be processed and examples of application to battlefied dynamics and to pollution spread in a river were presented .

All the above devices are information generators . Communication shall support the C3I network . Two papers addressed the question :

-for near term , Link 16 will equip most of the platforms involved in the aerospace C2 , and progress is underway to improve both the terminals and the message standards . Application to the extensions of Air Defense such as Theater Missile Defense is planned .

-the trend for the future is to aggregate more and more information sources , namely image , that will request adapted transmission media . From the military side , Information Highways are mandatory and the ATM (Asynchronous Transfer Mode) is the most probable protocole to optimally use the wide band channels , as it was discussed by the USAF .
The standard is now available and was successfully tested during exercises , but a lot of work has still to be done : error correction , network management , security , data compression , etc .

6)Conclusion and recommendations

The status of the currently ongoing activity on aerospace C3I, and many prospects were addressed during the symposium .
The description of the large integrated systems under development in NATO was clear; the trends towards mobility , integration of the COTS , and the relevant issues , including security were debated . The need for a methodology and tools to manage interoperability at systems of systems level was pointed out .
The status of the technical challenges : fusion of surveillance and of identification information seemed promising . The consistency of the efforts on databases management , including security issues has to be promoted .

Some information was provided on more future efforts . The integration of sophisticated intelligence and surveillance data in the process appeared critical , and examples of systems (satellites and airborne battlefield observation) were presented ; the role of modern communication systems for data transmission was addressed and the need for wideband communication was stressed .

We may suggest recommendations for possible future work and presentations under the direction of the Mission System Panel :

-address the integration of Aerospace C3I in the Extended Air Defense Concept , under analysis in Nato ; it would lead to new or modified sensor development , including passive and active IR , and to review critical timelines and C2 organization .

-as a consequence , critical issues such as target discrimination would be stressed as the main issue of ballistic missile defense . It will impact the design of the

surveillance and tracking architecture and sensors .

- the near real time integration and fusion of battlefield surveillance and intelligence data in the future will open questions about organization of the C2 : it obviously modifies the current relationship between planning , tasking and execution of the air force mission ; it requests adapted exchange of information and command and control responsibilities between the services who will share sensors , platforms and information ; the very short timelines from sensor to shooter will require an adaptation of the hierarchical C2 organization.

As a final suggestion , it might be worthwile to broaden the sources of the communications among the Nations ; several nations who are currently developping aerospace C3I relevant to the scope of the symposium did not propose contributions , that would have still enhanced the benefits of the meeting .

Tactical Role of Small Satellites

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The meaning of the expression tactical role within military scenery has extended largely during the last years. Any kind of intelligence activity or military intervention of international organisations, when necessary, usually is set up very early at the smallest sign of regional instability, long time before any word of war has been spoken out. Nevertheless, recent history has shown, that even though crisis with political and military threats to international order still can develop very rapidly at any time and at any place in the world. Therefore, the tactical role of any intelligence gathering system is starting to be measured at early stages of potential conflicts in terms of supporting features for the fulfilment of peacekeeping and peacemaking operations.

The tactical role for a space based system can be described with respect to the following four mission objectives. It is interesting to recognise, that they match with the decisionmaking cycle employed in the Marine Corps: Observe, Orient, Decide and then Act (OODA)

Environmental Monitoring
Treaty Monitoring
Crisis Monitoring
Precision Strike

For the case of environmental or treaty monitoring objectives, for example the support to verification for the chemical warfare disarmament, because mass destruction arms production projects are always wrapped in tight security and cover-up measures, space-based imaging with polar LEOs is perhaps the last remaining intelligence gathering means. We all know about which kind of resolution and technology we are talking about. The tactical role of such a system lies in the routined global surveillance operations that lead to confidence build-up processes between observing and observed forces.

The efficiency of this system depends highly on the technological level of the imaging sensors which do require a sophisticated AODCS (Attitude and Orbit Determination and Control System) and integrated ground processing and dissemination infrastructures. With the world wide reduction of military budgets, the Armed Forces are obliged to define new ways of doing their business. For such kind of global routine surveying missions the subcontracting of commercial imaging services, is more and more envisaged as a valid option to keep costs low, while more emphasis is given to the intelligence processing infrastructure on ground.

For the case of crisis monitoring, when early recognition of critical warnings such as arms build-ups is necessary, or when it is important to determine capabilities and intentions of the potential enemy, or finally, when the stage has been reached where military intervention over precision strikes is the only solution, then small satellites play its special tactical role in

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

communications, as an electronic mailbox for logistical issues world wide, or as remote sensing platforms that can be placed at any time and anywhere with latest technology and dedicated features (Area of interest (AOI), resolution, spectral bands, revisit time, refresh rates for intelligence information) The key words here are fast deployment, dedicated mission with latest technology level and of course the affordability.

Small satellites are not meant to replace large satellites, but they play a integral role within satellite constellations to support C3I. The employment of data relay satellites in the near future multiplies the intervention possibility of small satellites. With Pegasus or Taurus like launchers, for example, which are mobile launch vehicles with multiple small satellite capability, the possibility to set up a launch pad in 5 days and to integrate 2 small satellites with the launch vehicle and to launch within 3 days gives the possibility of specific AOI coverages with the latest sensor technology and flexible orbit plane architectures that comply with the precision strike strategies and the growing emphasis on tactical timelines. Remember the tactical role of the small communication link up satellites during the Desert Shield and Desert Storm. They worked as a backbone for logistical issues.

Today commanders want more. They want tactical reconnaissance, imagery, battle damage assessments, communications and operability, but donít forget, it must be affordable! As a crisis goes through different stages, a commander has time to put the hardware in position that collects information, stores or forwards in a way so that it can be processed, analysed, disseminated and finally delivered to him, so that he can decide what to do. The planing cycle for the field takes normally one week, while the refreshing cycle to gather intelligence information lies between 10 and 20 hours.

Small satellites may fit into these constraints and the question of affordability explains why they are getting increasingly important. They are the only way to have continuous and affordable testbeds for new technologies and training in space. Standardisation, multi purpose satellite bus technology with bolt-on payload philosophy and new integration concepts are being developed that lead to a reduction in the acquisition time, faster construction and to a higher space quality technological level and simpler ground operations.

EVOLUTION OF THE AIR COMMAND & CONTROL SYSTEM (ACCS)

TO MEET NATO'S NEW MISSION REQUIREMENTS

BY
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INTRODUCTION

As the ongoing crisis in the former Yugoslavia has made clear, NATO's support to crisis management operations depends first and foremost on air power. Effective use of air power requires an integrated, interoperable command and control system that controls all tactical air operations. A single command and control structure is required to provide the planning and tasking of offensive, defensive and support air operations. The system must be flexible and able to respond to changes in priorities as the crisis or conflict evolves and it must provide a deployable capability to support out-of-area operations.

The NATO Air Command and Control System (ACCS) Programme has been redefined in response to this challenge.

SITUATION TODAY

Today the NATO Integrated Air Defence System, which has served the Alliance from the 50's provides command and control for defence air operations from northern Norway to eastern Turkey and is made up of regional systems as shown here. Separate national systems provide the command and control for offensive air and support missions. During the mid-1970's it was concluded that the NATO Air Defence Ground Environment System (NADGE) was quickly becoming obsolete and required radical modernization and in 1979, the Defence Ministers approved a programme to meet the need for an integrated Air Command and Control System for the full spectrum of tactical air operations; defensive, offensive and support.

EARLY PLANNING

To carry out this programme, a team of national experts developed and produced, in 1989, a document called the ACCS Master Plan. The Plan was developed to meet NATO's perceived needs at that time. From the start ACCS was to be a combination of NATO and national assets, and included all the surveillance, communications and information exchange required for an integrated system. The concept at that time also envisioned a large number of surveillance sensors, and many fixed command facilities, most of them housed in bunkers. Additionally, the nations experts also laid the ground work for the transfer of responsibility for the planning and implementation of the ACCS Programme to the new ACCS Agency, thus the NATO ACCS Management Agency, NACMA was established in January 1991.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

CHANGES FOR THE 90's

Since the London Declaration of 1990, the Alliance has steadily reshaped itself into a new NATO. NATO's new Strategic Concept was agreed at the Rome Summit in 1991. Specifically, the concept called for increased emphasis on crisis management and peacekeeping and for increased co-operation and dialogue with the emerging democracies of Central and Eastern Europe. Moreover, it was recognized that NATO could fulfill its new roles with smaller, more flexible forces. It took four or five reviews to reshape the ACCS Programme to keep it aligned with the new NATO strategy and reduced budgets. Emphasis is now placed on flexibility, deployability and interoperability. The Programme now consists of only a backbone of in-place facilities, and sensors which together provide the in-place command, control and surveillance capability, for peacetime and early crisis requirements. A Deployable ACCS Component or DAC has been included to meet the wartime requirements, and provide the flexibility to conduct out-of-area peacekeeping operations.

OPERATION REQUIREMENT

SACEUR has the responsibility for air defence of NATO Europe in peace, crisis and war. This requires an integrated air defence system with appropriate sensors, command and control and weapon systems to obtain and maintain a favourable air situation, coordinated as necessary with maritime forces. The planning and tasking of air operations requires the integration of defensive, offensive and support operations and there needs to be a single command and control system to guarantee the correct employment. Significant air reinforcements to any crisis or conflict must be matched with the deployment of a complementary command and control capability. Such a deployment will be most critical to support NATO commitments or reaction forces, and to support peace operations; including the deployment of the Combined Joint Task Force or any operation under a Western European Union, United Nations or other mandate should such a political decision be made. The deployable capability could also support exercises or other missions under the Partnership for Peace Programme.

THE ACCS PROBLEM

Conceptually, the long-term architecture of ACCS is shown here. The operational requirement requires an integrated air command and control system which permits a high degree of interoperability, and which in addition, will allow interoperation with other surveillance assets both NATO and national and with land and maritime forces. The approach taken is to establish a minimum backbone of static command and control sites and sensors within Allied Command Europe together with France and Spain, which will provide for peace and early crisis operations. It is then planned that the deployable ACCS component and the NATO Airborne Early Warning Force will augment the backbone in any area of crisis or conflict. The concept also envisions the future integration of the Alliance Extended Air Defence Capability against Tactical Ballistic Missiles and Cruise Missiles and the integration of the ground segment for Ground Surveillance. Of course these future capabilities depend on the political decisions made in these areas.

LEVEL OF OPERATIONAL CAPABILITY

To allow for such a wide range of functions, it was decided to implement an evolutionary acquisition strategy which we call Level of Operational Capability to the extent allowed under the NATO acquisition procedures. For LOC1; which is the current implementation programme; our objective is to provide for a timely solution and one that is affordable and represents low technical risk. Therefore we have scoped the LOC1 procurement specification such that the solution can be provided by already proven technology. Our general approach is to integrate functions already automated, and use as much existing software; including COTS and communications as possible. The main challenge is to provide a fully integrated system, fulfilling the requirements of modularity, portability and reusability through an open system architecture.

ACCS ARCHITECTURE

Shown here are the entities that comprise LOC1. We will first acquire the system software. Thereafter, a number of static and deployable Combined Air Operation Centres will be established to accommodate the planning and tasking function, as well as the coordination with land and maritime forces. Further, a number of static and deployable Air Control Centres and surveillance facilities will be established to control air missions, using a comprehensive Recognized Air Picture, based on input from static and deployable radars including the NAEW, maritime assets, intelligence and civil air traffic control. Finally, the other entities, which are national responsibility include the national wing, squadron, and SAM operation centres.

COMBINED AIR OPERATIONS CENTRE

The Combined Air Operations Centre, CAOC exercises tactical command and control over allocated air assets, and performs all air mission tasking, and coordination with land and maritime forces.

AIR CONTROL CENTRE/AIR CONTROL UNIT

The Air Control Centre, Air Control Unit, (ACC/ACU), is the real-time battle management entity. It provides the real-time control of air missions in a designated area. It provides Surface to Air Missile (SAM) weapon preparation, and is responsible for the co-ordination with NAEW and weapon control operations.

RECOGNIZED AIR PICTURE PRODUCTION CENTRE

The Recognized Air Picture Production Centre is responsible for producing and disseminating the Recognized Air Picture (RAP). The identification function along with data from non-ACCS sources, such as NAEW and Air Traffic Control are incorporated at the RPC.

SENSOR FUSION POST

The Sensor Fusion Post (SFP) provides sensor management and produces tracks from active and passive sensors.

OPERATIONAL VALIDATION

Following the software acquisition and testing at the System Test and Validation

Facility (STVF), we will conduct operational testing at four operational sites in Belgium, France and Italy shown here. The designation of ARS and CARS, indicates that an ARS is the co-location of an ACC, RPC, SFP and a CARS is the co-location of a CAOC, ACC, RPC, and SFP.

DEPLOYABLE CAOC

Also CAOC Uedem is being configured as a hybrid installation such that a number of the work stations will be provided in shipping containers such that a short notice deployable CAOC capability can be provided.

INITIAL REPLICATION

Following operational test and validation the system will be replicated at 12 additional sites shown here. Again you will notice that all entities will be co-located except for the CAOCs at Reitan, Finderup, and Uedem.

DEPLOYABLE ARS

In addition to these fixed locations, we will also produce a deployable ARS as part of the system replication.

INITIAL CAPABILITY PACKAGE

The estimated cost for software and testing at the STVF is about $152 million (38MIAU); Integration into the four validation sites is about $ 140 million (35MIAU), plus about $24 million (6MIAU) for civil works. The 12 replication sites are estimated at $288 million (72MIAU) plus $112 million (28MIAU) for civil works. The deployable entities are estimated at $100 million (25MIAU). This represents $81 million to be funded from the common NATO Security Investment Programme. In addition, some $600 million of national projects are in the Capability Package for Wing and Squadron Operation Centres; Air Operation Co-ordination Centres and Surface-to-Air Missile Operation Centres. Although these costs exceed the nominal guidelines for Capability Packages, the North Atlantic Council approved the Programme on 11 May 1994. The TBCEs for the software, STVF and Validation sites are currently being screened by the NATO Infrastructure Committee. The only major issue is Industrial Benefit Sharing. Assuming financial authorization we will release the IFB to industry before the end of 1995, most likely in November, Contract Award should take place by early 1997.

CONCLUSION

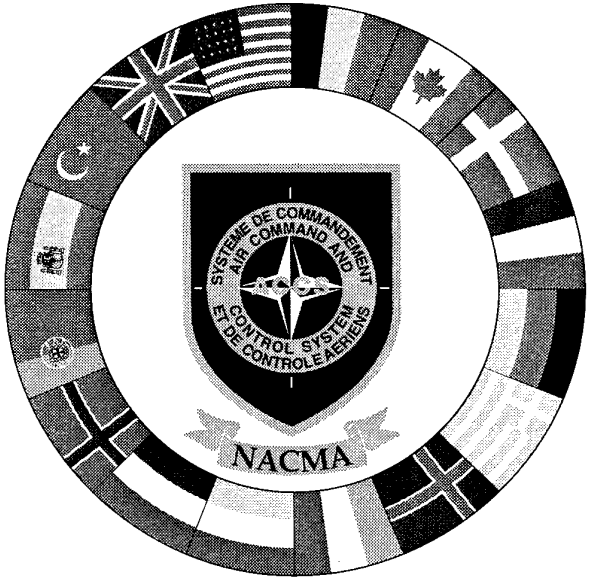
The initial ACCS Capability Package, developed in close coordination with SHAPE, represents the minimum military requirement, and is the result of several programme reviews conducted these past years. The programme takes account of the outcome of the debate on the new Alliance strategy, force and command structure and the fundamental review of the infrastructure programme.

The ACCS architecture provides flexibility and modularity to enable the system to change or grow as the requirements and situations change. The common software will allow nations to have a common capability, thereby allowing standard procedures to be developed. ACCS ensures that SACEUR will be able to continue to fulfill his air defence mission and to adequately direct and control other air missions for a wide range of peace time

and crisis operations. The NATO integrated Air Defence System has been a central pillar of cooperation among the Alliance nations for many years ---. The ACCS programme continues this cooperation.

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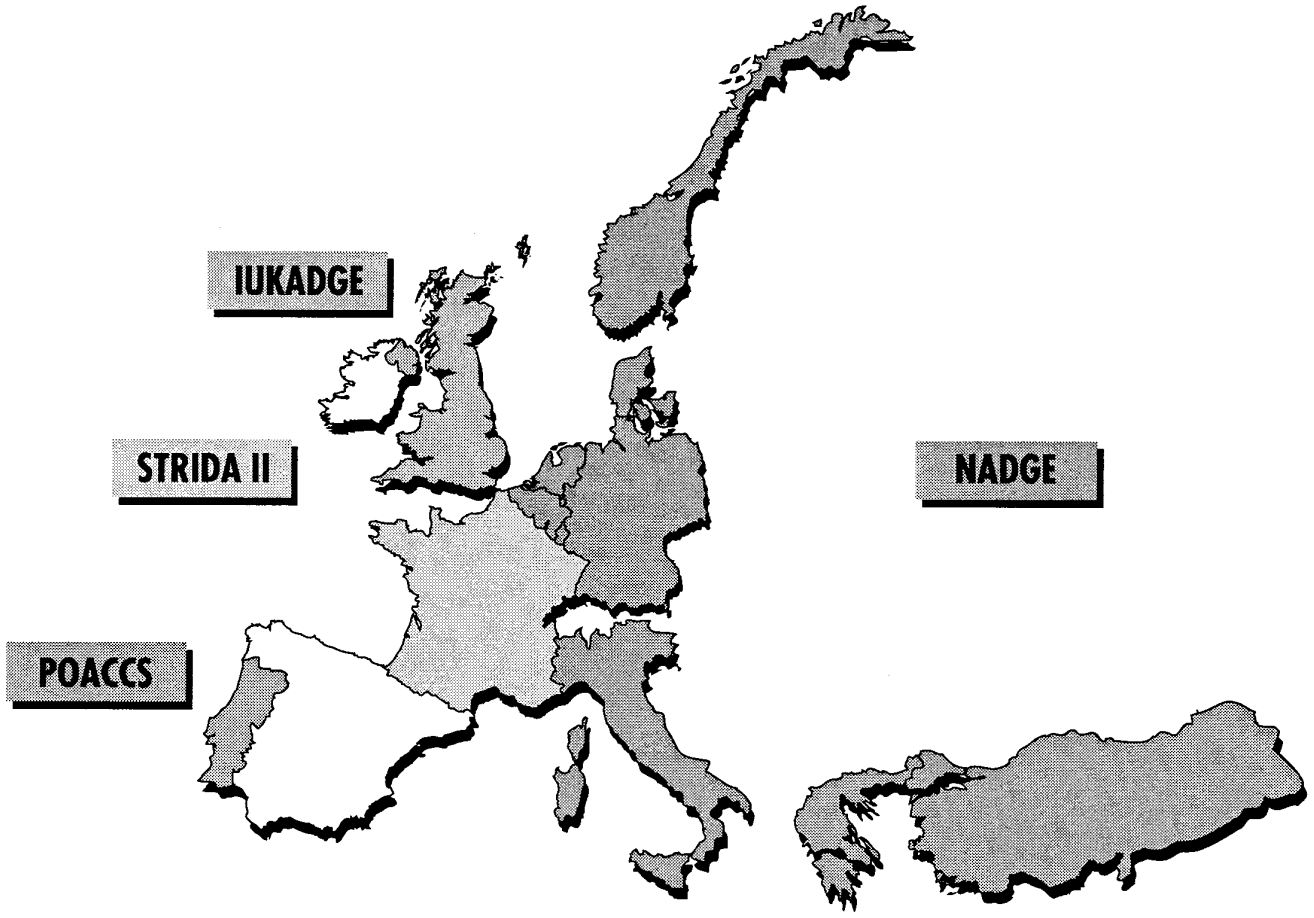
NATO AIR COMMAND AND CONTROL SYSTEM (ACCS)



Robert Giacomo

NACMA, General Manager

NATO ACCS - Regions/Systems



KN2-7

ACCS Planning Started in the 80's

The ACCS Team ➡ The ACCS Master Plan

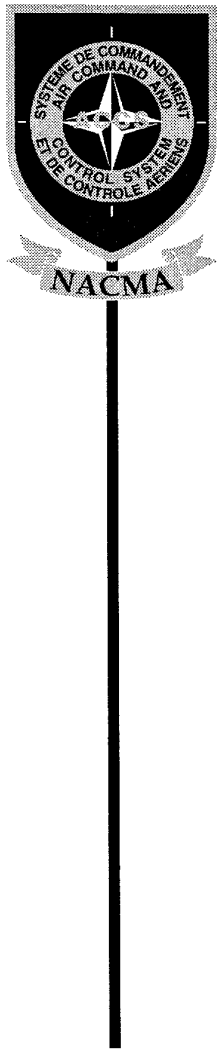
- *NATO and National Assets*
- *Communications*
- *Information Exchange*

NACMA established January 1991



Changes for the 90's

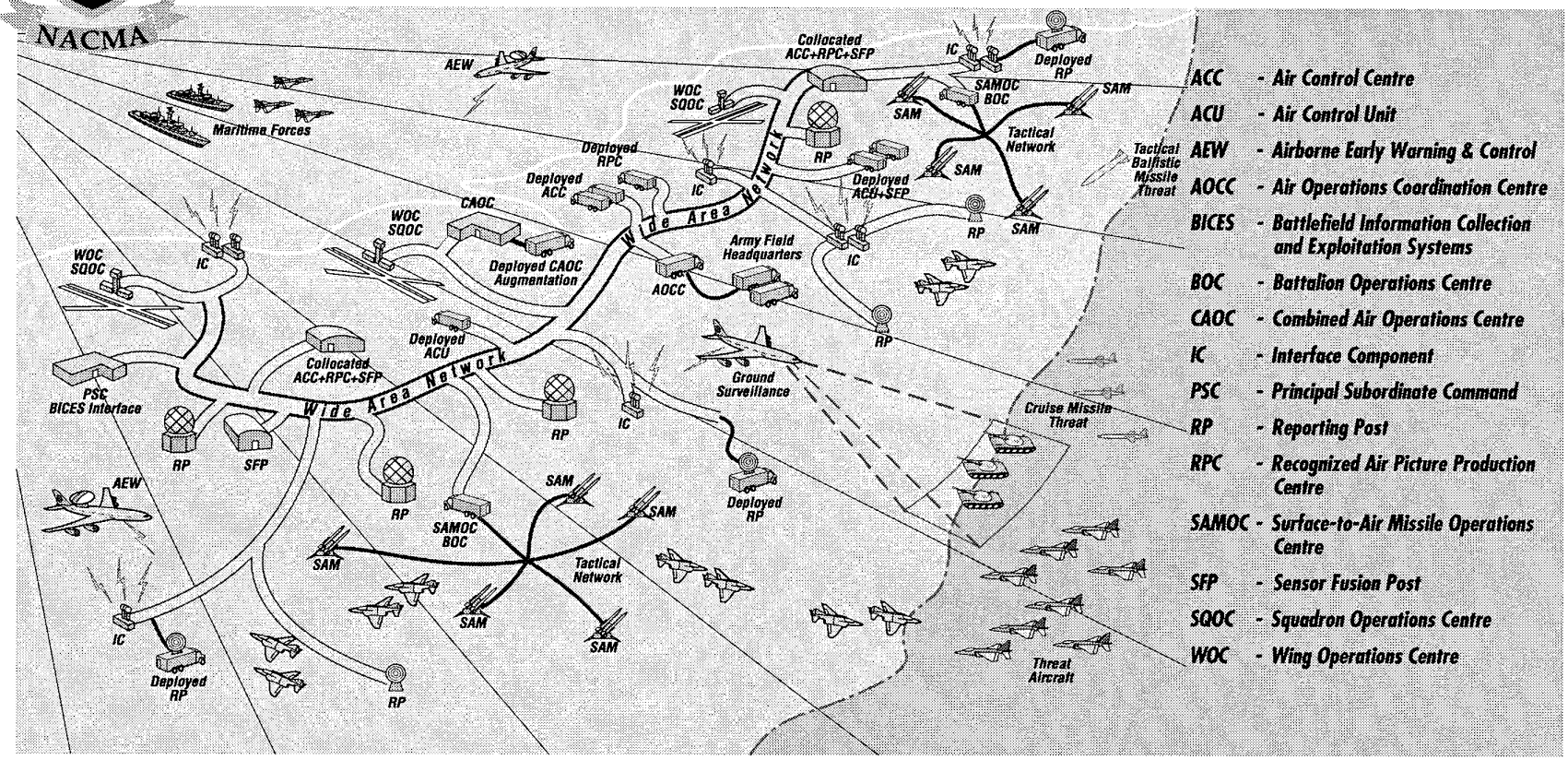
- End of the Cold War
- NATO forces decrease
- NATO budgets decline
- New Alliance Strategy
- New NATO ACCS
  - *More Mobile*
  - *Less Costly*



The Operational Requirement

- Air Defence of NATO Europe
- Planning and Tasking of Air Operations
- Deployable Capability
  - *Support to Reaction Forces*
  - *Peacekeeping Operations*
  - *Combined Joint Task Force*
  - *Partnership for Peace*

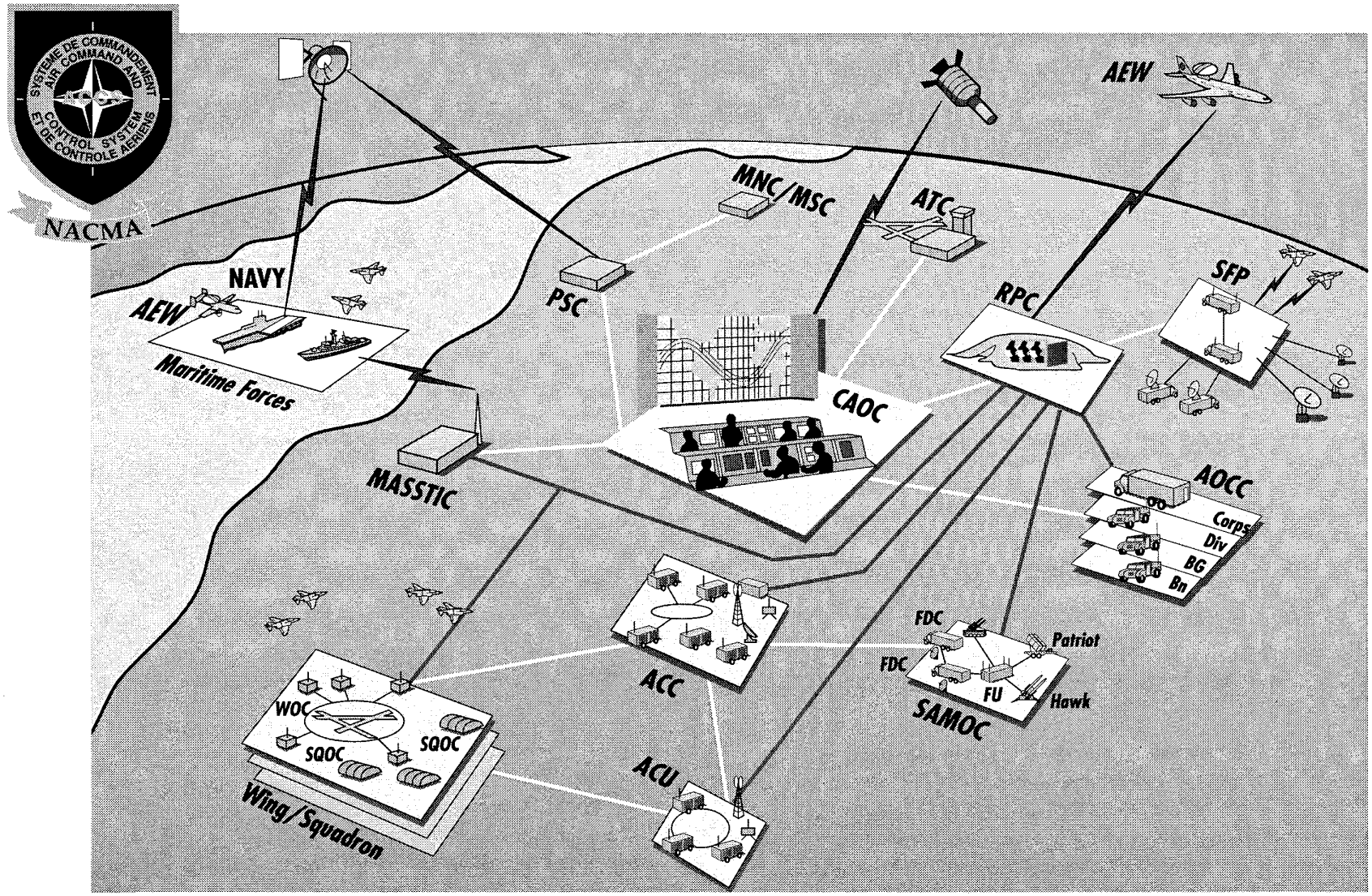
ACCS ARCHITECTURE





Level of Operational Capability
(LOC1)

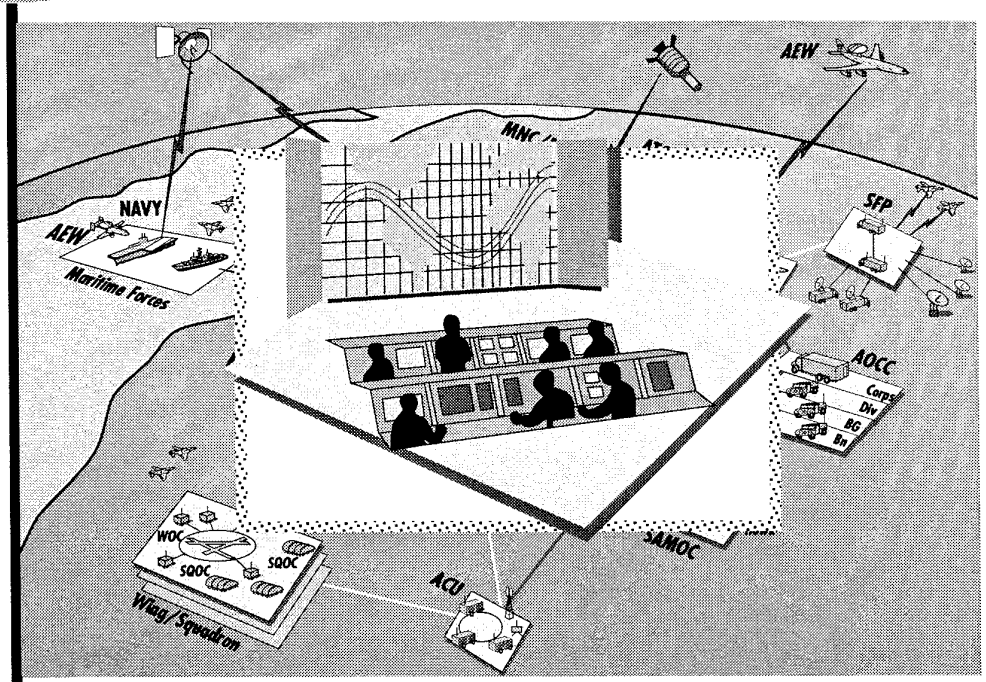
- Integrate functions already automated
- Use existing software where possible
- Use commercial off-the-shelf software
- Use existing communications
- Provide Information Exchange



SLIDE 8

KN2-13

Combined Air Operations Centre (CAOC)



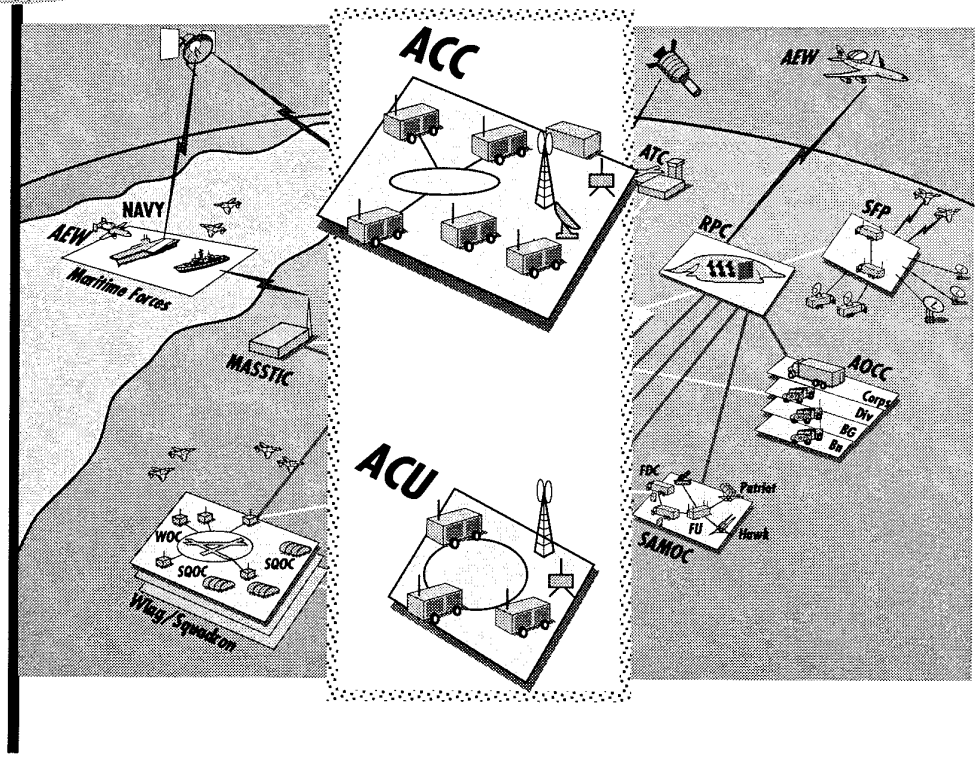
Mission

- *Plan*
- *Allocate Resource*
- *Task OPS*
- *Monitor OPS*

Functions

- *Offensive Tasking*
- *Support Tasking*
- *Defensive Tasking*
- *Airspace Control Planning*

Air Control Centre/Unit (ACC/ACU)



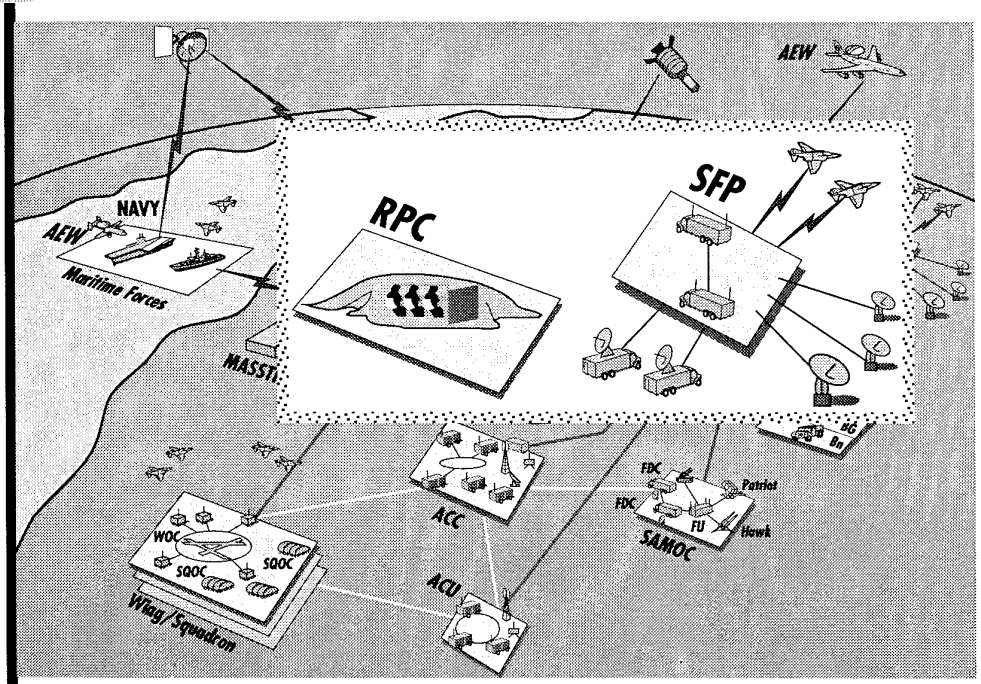
Mission

- *Airspace Control*
- *Control Missions*
- *Control Weapons*

Functions

- *Air Mission Control*
- *SAM Mission Control*
- *Air Traffic Control*
- *SAM Weapon Preparation*

Recognised Air Picture Production Centre *(RPC)*



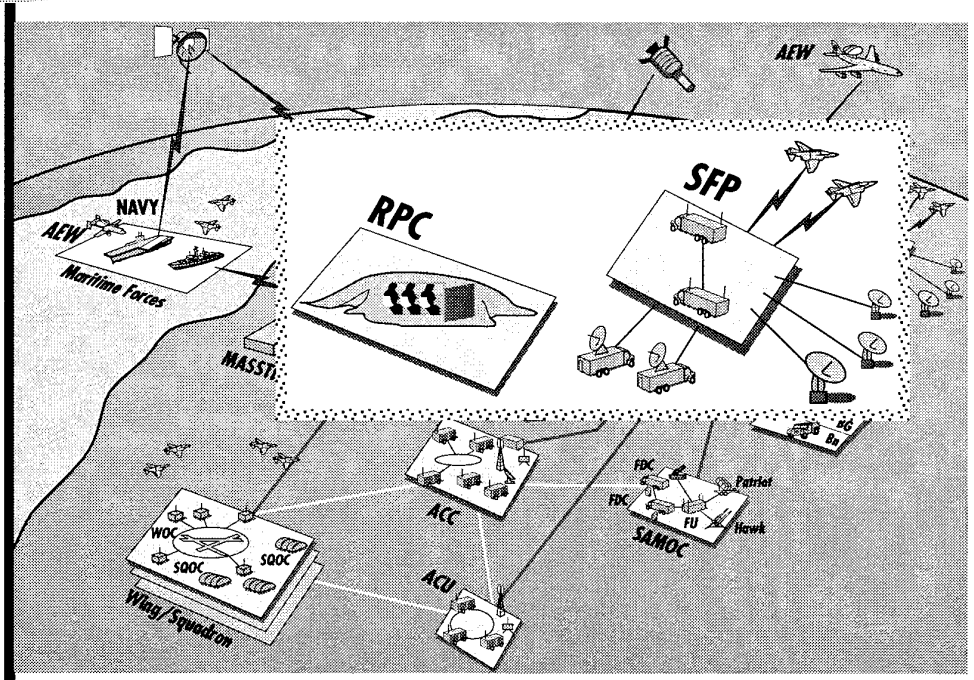
Mission

- *Survey the Region*
- *Plan/Control Sensors*
- *Aggregate Sensor Input*

Functions

- *Establish Air Picture*
- *Manage Surveillance*
- *Disseminate The RAP*

Sensor Fusion Post
(SFP)



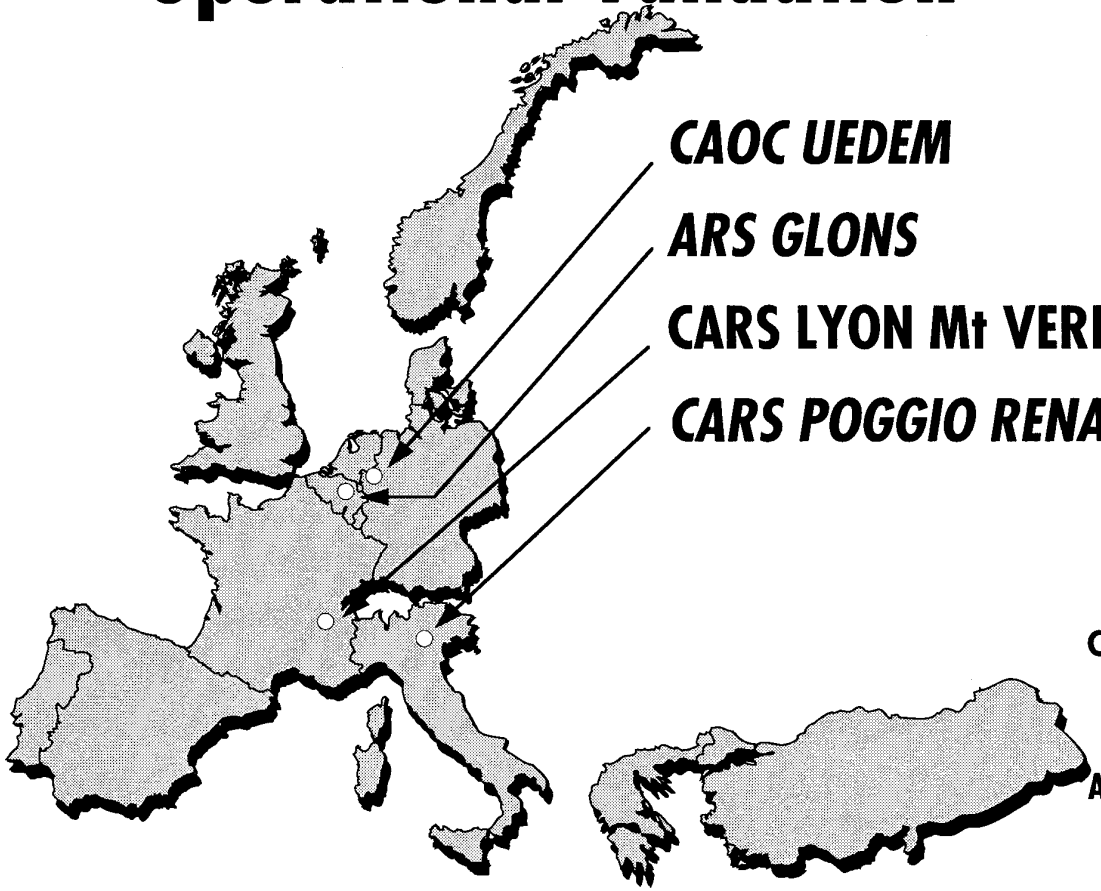
Mission

- *Produce Local Air Picture*
- *Integrate Variety of Sensors*
- *Perform Multi-Sensor Tracking*

Functions

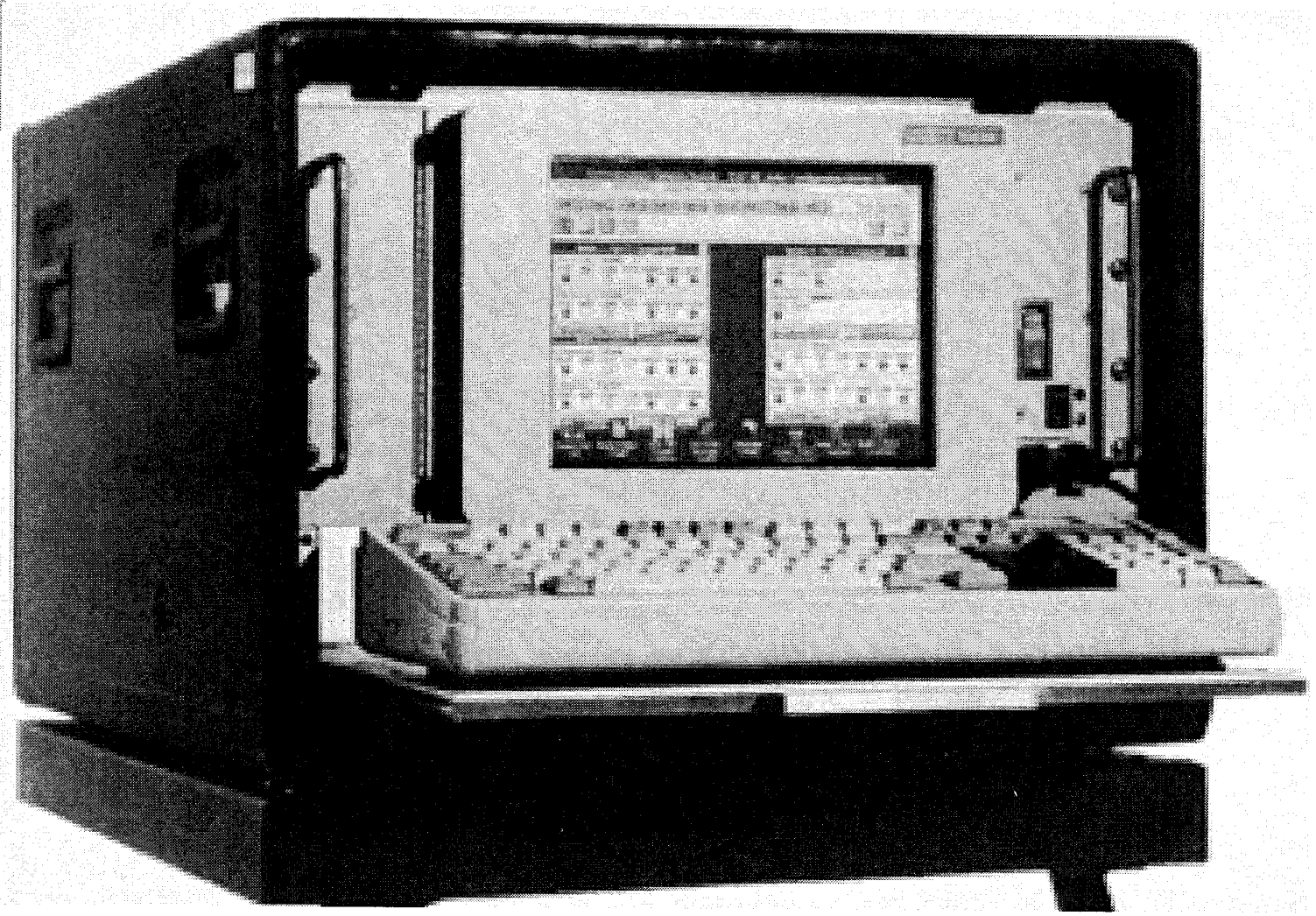
- *Fuse Sensor Data*
- *Manage Local Sensors*
- *Coordinate with Adjacent SFPs*

NATO Europe
Operational Validation



CARS = Collocated CAOC, ACC, RPC, SFP

ARS = Collocated ACC, RPC, SFP

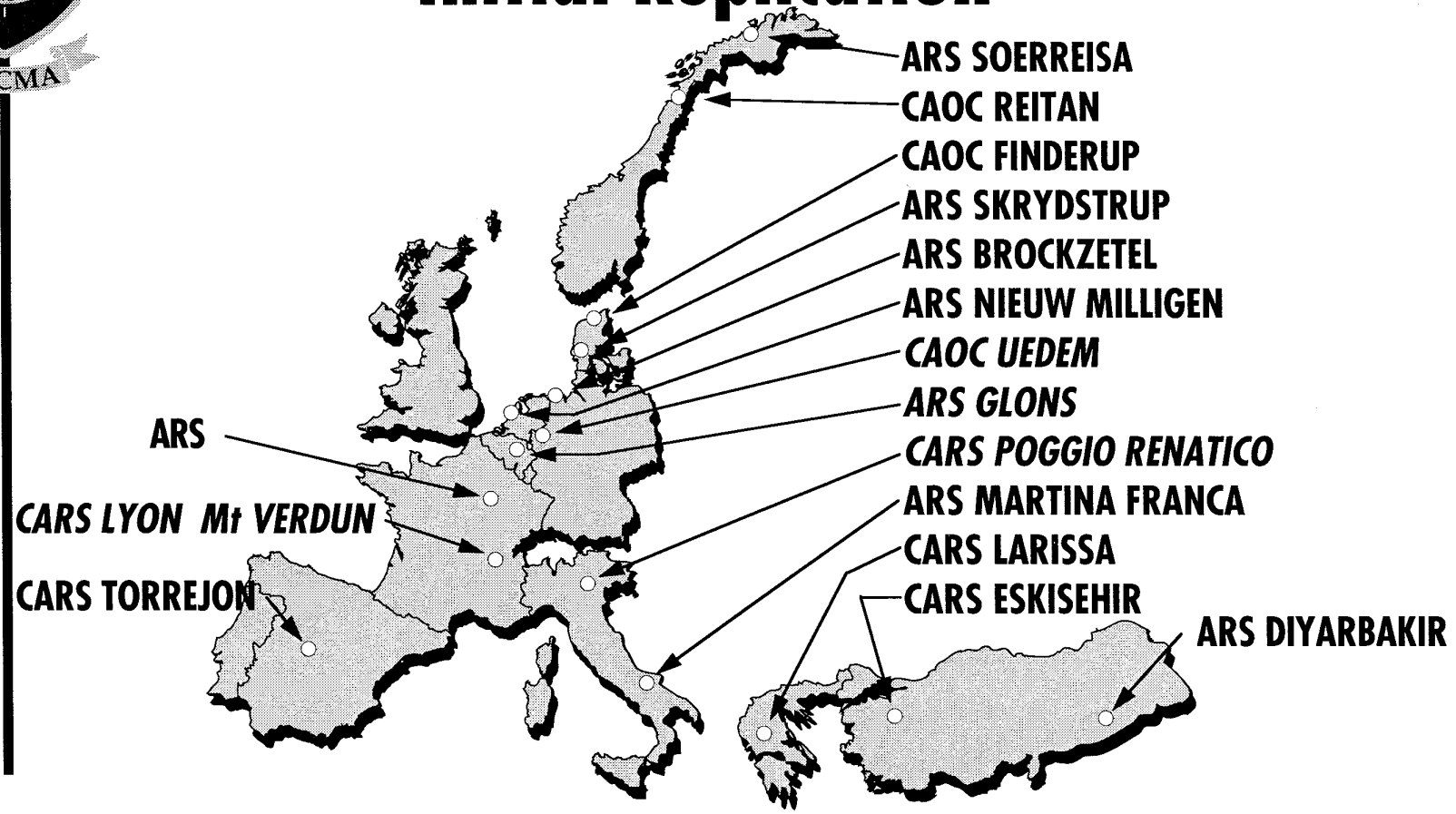


SLIDE 14

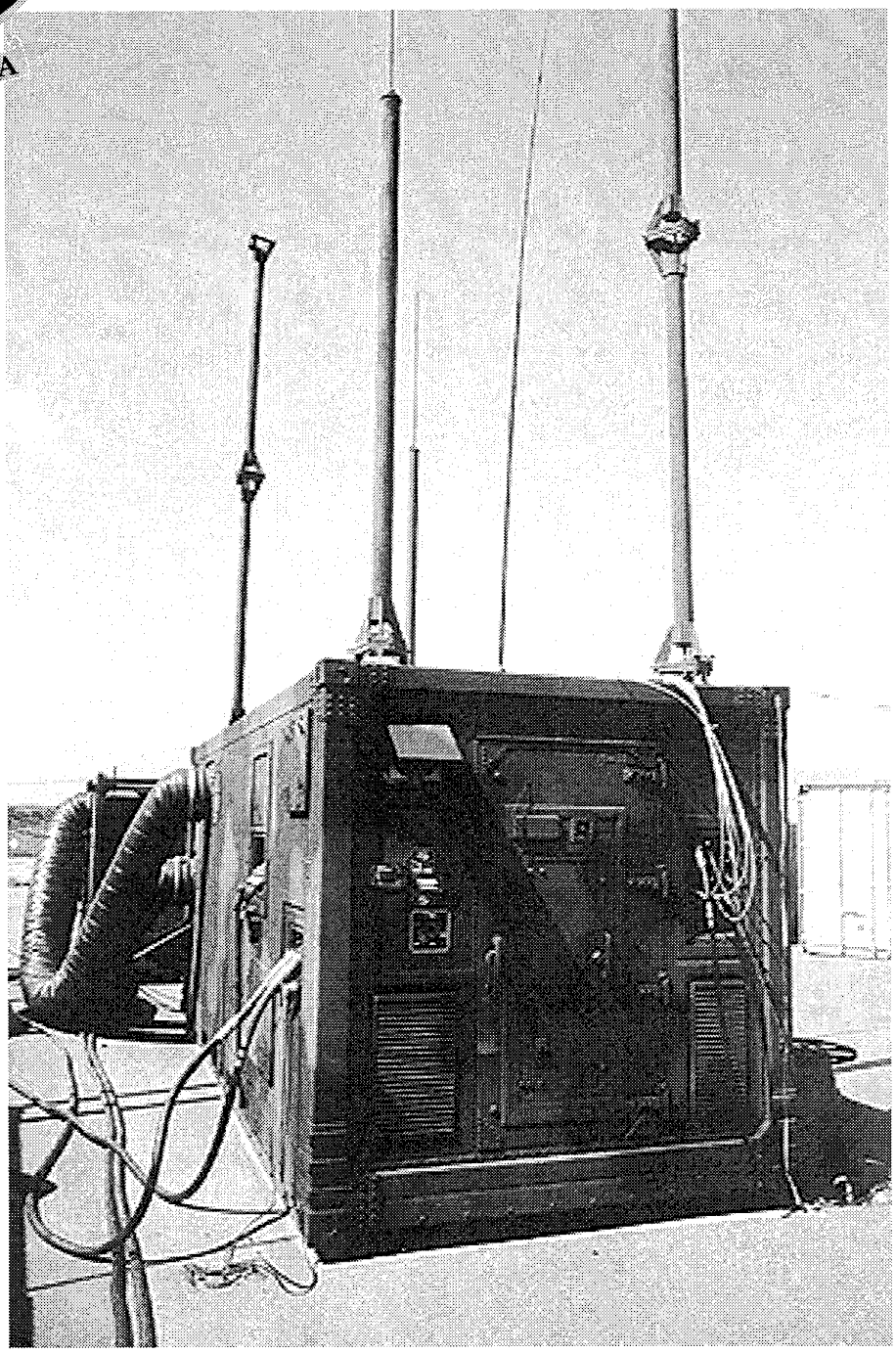
KN2-19

NACMA

NATO Europe
Initial Replication



NACMA



SLIDE 16

Status of the Initial ACCS Implementation

- Approved by Council, 11 May 94
- TBCEs for SW, STVF & Validation Sites
- NACMA procurement agent for replication
- Territorial Nations responsible for civil works and external communications
- IFB Release before the end of 1995
- Contract award late 1996 early1997

Conclusion

- **Completion of ACCS LOC1 will take 6 to 8 years**
  - *Software and testing at the STVF* *2000*
  - *Operational testing at Validation sites* *2001*
  - *Installation of Initial Replication sites* *2002*
  - *Installation of Follow-on Replication sites* *2004*
- **Measures to maintain required operational capabilities**
  - *Minor Works Projects*
  - *Stand-alone projects*
  - *Follow-on Capability Packages*

Le programme SCCOA: le besoin de l'Armée de l'Air et son développement technique

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La décision de créer pour le SCCOA, un programme d'ensemble a été prise le 15 février 1989.

Un dossier d'orientation d'ensemble a été finalisé le 17 décembre 1991 et a permis de lancer les premiers contrats SCCOA.

Une première étape, SCCOA1, a fait l'objet d'un DLR, Dossier de Lancement de la Réalisation le 15 février 1993.

Après l'exposé de l'officier de programme sur les besoins opérationnels de l'Armée de l'air, je vais vous présenter les problèmes posés à l'ingénieur. Je commencerai avec la description technique du contenu du programme en relevant les aspects systèmes qui motivent la création d'un programme unique pour couvrir l'ensemble des SIC de l'Armée de l'air.

Je vais vous présenter ensuite les enjeux méthodologiques qu'un programme d'ensemble tel que le SCCOA peut présenter pour la DGA en tant que maître d'oeuvre et plus généralement pour ses concepteurs et réalisateurs que vous représentez largement aujourd'hui.

Je voudrais tout d'abord revenir sur la question : Pourquoi un programme unique pour l'ensemble des moyens de commandement et de contrôle au sol de l'Armée de l'air ?

Le Colonel BEAUGNON a déjà donné quelques bonnes raisons avec la nouvelle organisation de l'Armée de l'air et l'unicité du commandement.

Il y a aussi des motivations à caractère plutôt technique et méthodologique qui ont conduit à prendre la décision de 1989 de créer un programme unique : logiciels de plus en plus volumineux, développement de nombreux systèmes d'information et de communication, propres à l'Armée de l'air, ou en interface avec elle, difficultés de prendre en compte l'existant et de gérer ses évolutions de manière cohérente.

Je prends en exemple l'histoire du STRIDA, système de traitement et de représentation des informations de défense aérienne. Le STRIDA a été créé dans les années 60 pour traiter les informations des grands radars de défense aérienne. Notons au passage que dès cette époque la notion de système d'information était déjà acquise.

Nous avons raccordé progressivement au STRIDA les informations des radars civils, puis celles des radars des bases aériennes. Plus récemment nous avons introduit les liaisons avec les batteries de défense sol-air, avec le système de défense aéroporté (les AWACS), avec les avions Mirage 2000 par le téléaffichage. Cette histoire illustre bien la croissance de la complexité des systèmes. Elle montre aussi tout l'intérêt d'un système ouvert et évolutif pour pouvoir accueillir sans trop de difficultés des extensions nouvelles.

Le contenu physique du SCCOA se décompose traditionnellement en trois grandes rubriques : les moyens de détection, les transmissions, l'informatique.

Cette planche présente les moyens de détection actuels sur la colonne de gauche et à droite ceux qui pourront être déployés à l'avenir.

Les moyens de détection actuels doivent être modernisés et complétés. L'aviation civile abandonne la détection primaire et nous aurons besoin dans certaines zones d'installer de nouveaux radars 23 cm. Des radars haute fréquence trans horizon ou RIAS pourront compléter la couverture en bande S et en bande L, notamment vis-à-vis des cibles à faible surface équivalente radar. Pour la basse altitude, le système de détection aéroportée (les AWACS) est bien sûr la pièce maîtresse mais les systèmes sol gardent leur intérêt pour des zones ponctuelles.

Une approche système est nécessaire, dans le domaine de la détection, pour optimiser la couverture radar, le fonctionnement en modes dégradés ou en cas de brouillage, la protection contre les missiles antiradars et bien sûr pour la gestion des fréquences, surtout si l'on veut introduire des radars dans les bandes haute fréquence.

A l'avenir, si une défense aérienne élargie est constituée, les informations issues des moyens de détection devront être transmises au centre de commandement et de contrôle des opérations aériennes.

Les transmissions évoluent vers des systèmes à haut débit et mieux protégés contre les compromissions : Have Quick II, UHF durcis, le MIDS-liaison 16. Des liaisons nouvelles sont développées pour relier les systèmes aéroportés et les centres de contrôle fixes ou mobiles.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

Les aspects systèmes ne concernent pas que le SCCOA mais tous les systèmes utilisateurs. Une bonne coordination est donc nécessaire entre les différentes directions de programme concernées. Les réseaux sol-air, par exemple, concernent tout autant les aéronefs, français et alliés et aussi certaines plates-formes de la Marine et de l'Armée de terre. Les réseaux de transmission des bases aériennes seront modernisés. Bien entendu les problèmes de partage du spectre électromagnétique, d'allocation et de gestion des fréquences nécessitent des études systèmes rigoureuses.

C'est dans le domaine des systèmes d'informations que les aspects systèmes sont les plus importants en volume. Ce domaine est encore appelé traditionnellement "informatique" dans notre vocabulaire, mais un système d'information ne se réduit pas à un système informatique, comme chacun sait.

La planche qui vous est présentée maintenant schématise l'articulation de l'ensemble des grandes fonctions du SCCOA telles qu'elles ont été décrites par le Colonel BEAUGNON : surveillance, évaluation de la menace, gestion de l'espace, gestion des forces et des moyens, contrôle des missions, contrôle du trafic, exploitation du renseignement.

On peut distinguer deux boucles principales :

- une boucle que l'on peut qualifier de "temps réel", avec la surveillance aérienne et le contrôle des missions,
- une boucle "commandement" avec le renseignement et l'élaboration de l'ordre de bataille ennemi, l'état des forces et des moyens, la planification, l'attribution, la préparation des missions.

On voit que ces deux boucles sont très interdépendantes et qu'il faut assurer leur interopérabilité, ainsi que l'interopérabilité des différents systèmes qui les constituent.

Il est bien évident aussi que l'Etat-major des Armées, la Marine et l'Armée de Terre ont besoin d'échanger des informations ou d'envoyer des directives, et que des interfaces sont à prévoir à différents niveaux.

L'interopérabilité avec les alliés, c'est-à-dire avec l'ACCS est aussi une demande incontournable, de même qu'avec le contrôle aérien civil.

Le Colonel BEAUGNON a déjà présenté les principales interfaces du SCCOA.

Je veux seulement souligner que le problème des interfaces n'est pas seulement une question de standards techniques d'échanges, il s'agit aussi de mettre au point des procédures d'échanges d'informations et même d'échanges de responsabilités entre des acteurs, on intervient donc dans leurs méthodes de travail, quand ce n'est pas sur leur organisation interne ou leur hiérarchie, le problème est bien connu dans l'industrie lorsque l'on veut développer un système d'information. C'est cela la véritable interopérabilité. Aujourd'hui, cette inter-opérabilité est maîtrisée de façon bilatérale, de SIC à SIC ; il n'y a pas d'interopérabilité globale. Si l'on veut éviter de multiplier les interfaces d'une manière combinatoire et exponentielle, il faut avoir une approche globale.

Où en sommes-nous aujourd'hui ?

La boucle temps réel est déjà largement couverte avec le STRIDA, mais le STRIDA lui-même doit évoluer techniquement, aussi bien pour renouveler les matériels que pour mettre à jour les logiciels, notamment vis-à-vis des normes de qualité et des standards du marché.

Pour le reste, on a déjà ponctuellement réalisé certains SIC ainsi que plusieurs systèmes de préparation de missions, mais ces systèmes restent parcellaires et ne couvrent qu'une partie des besoins. Il s'agit donc de continuer à développer les différents SIC concernés mais d'une manière cohérente et intelligente si l'on veut en final avoir non pas une coexistence difficile entre eux mais un véritable système de gestion de la bataille ou de gestion de crises.

N'oublions pas que la boucle de commandement existe déjà, mais fonctionne de manière encore très manuelle, si l'on peut dire (téléphone, télécopie, transmissions d'images sont déjà largement utilisés). Il s'agit d'apporter les aides informatiques qui permettront de faire circuler l'information plus rapidement, donc d'obtenir un temps de réaction globale beaucoup plus court et de gérer un nombre très élevé de missions/jours.

A ce stade de l'exposé, je peux déjà présenter une synthèse des principaux axes de travail :

- donner à l'Armée de l'air les moyens dont elle a besoin dans le cadre de sa nouvelle organisation et de ses nouvelles missions, d'où la priorité donnée aujourd'hui au développement des moyens mobiles,
- fédérer un existant considérable, notamment, faire évoluer le STRIDA vers une architecture modernisée et compatible avec l'ACCS,
- introduire des fonctions nouvelles tout en assurant la cohérence d'ensemble, surtout dans les fonctions de commandement,
- assurer l'interopérabilité, interarmées et interalliées ; l'interopérabilité avec l'ACCS est sans doute la contrainte la plus structurante sur les fonctions opérationnelles et le découpage des modules logiciels.

COMMENT FAIRE ?

Je voudrais maintenant vous présenter la méthodologie que l'on a commencé à mettre en place à la Direction de programme, avec l'aide de l'Architecte Industriel, pour gérer cette affaire en introduisant de la rigueur, mais en voulant rester pragmatique.

Introduire de la rigueur, c'est appliquer les directives en matière de conduite des programmes d'armement, avec un découpage en phases et jalons. Mais il est difficile d'appliquer brutalement ce concept pour traiter l'ensemble du problème posé.

En fait, c'est pour chacun des constituants du SCCOA que nous cherchons à appliquer la méthode, et ces constituants sont très nombreux. Nous avons appelé "opération technique", étude, réalisation ou maintien en condition opérationnelle, un ensemble de tâches cohérent entrant dans le cycle de vie d'un tel constituant.

Ces opérations techniques sont regroupées en étapes cohérentes. Nous avons ainsi une soixantaine d'opérations techniques au titre de l'étape 1 du SCCOA. Les étapes se succéderont tous les 2 ou 3 ans pour réaliser des versions successives du SCCOA. Qu'est ce qu'une étape ? Qu'est ce qu'une version ?

Une version du SCCOA forme un tout cohérent sur le plan opérationnel, elle couvre l'ensemble du système et détermine le contexte d'emploi de ses constituants.

En termes de qualité et de gestion, une version se prépare, se spécifie, se qualifie, a une définition.

En pratique, on passera d'une version à la suivante de manière progressive et contrôlée au plan du contenu technique, des coûts et des délais.

La réalisation des versions successives se chevauchent nécessairement puisqu'on lance une version tous les deux ou trois ans, alors que le développement de chaque constituant couvre une période de 5 à 10 ans.

C'est une manière d'appliquer les recommandations relatives aux programmes à logiciels prépondérants qui préconisent le développement "incrémental" pour éviter les divergences inacceptables entre les besoins des utilisateurs et la perception qu'en ont les réalisateurs.

On regroupe donc les opérations de manière transversale, par étapes ; chaque étape regroupe des opérations techniques :

- de réalisation de la version N,
- d'études pour préparer la version N + 1,
- de maintien en condition opérationnelle de la version N - 1.

Tout cela nécessite comme vous pouvez l'imaginez de mettre en place une gestion de configuration adaptée aux besoins : au besoin de l'Armée de l'air qui doit savoir à tout moment quelle est sa configuration ou son standard opérationnel ; au besoin du maître d'ouvrage et des industriels réalisateurs ou concepteurs lorsqu'il s'agit de préparer les contrats ou d'aller travailler sur les installations existantes.

Les systèmes C3I de l'Armée de l'air sont conçus et réalisés sous la responsabilité du Service Technique des Télécommunications et des Equipements aéronautiques, le STTE, qui s'est donc vu confier naturellement la conduite du programme SCCOA.

La maîtrise d'oeuvre des réalisations individuelles est confiée aux industriels les plus compétitifs ; pour l'ingénierie globale du système, il a été décidé de faire appel à un architecte industriel indépendant des maîtres d'oeuvres et des réalisateurs : AEROSPATIALE.

Dans le schéma désormais classique du "V" méthodologique, l'architecte industriel est responsable de l'architecture d'ensemble, il a conduit l'analyse fonctionnelle en cohérence avec celle de l'ACCS ; cette analyse a permis de décrire précisément chacune des 8 fonctions du SCCOA que le Colonel BEAUGNON vous a présentées. L'architecte réalise les conceptions systèmes jusqu'aux spécifications techniques de besoin globales des produits.

Un point que cette planche ne fait pas apparaître est le rôle de l'Armée de l'air. Si l'on veut éviter les divergences entre les besoins de l'utilisateur et les réalisations, lorsqu'il s'agit de systèmes d'information, il est indispensable d'organiser des retours fréquents (disons tous les 6 à 18 mois maximum). A chaque phase du développement, il faut organiser de tels rebouclages. C'est ce que certains appellent IBO, illustrateur de besoins opérationnels, en phase de faisabilité, maquettes/prototypes en phases de définition détaillée, plate-forme d'essais et d'intégration au stade de la réalisation. Ces rebouclages ne sont pas prévus formellement dans l'instruction sur la conduite des programmes d'armement, ni dans la planche qui vous est présentée mais ils doivent faire partie des règles de management d'un programme tel que le SCCOA.

Une plate-forme d'intégration à Mont-de-Marsan, le Centre de Développement, d'Evaluation et de Validation des Systèmes (CDEVS) a été d'ailleurs prévue pour réaliser les essais des sous-ensembles dans un environnement opérationnel réaliste, et pour valider les grandes fonctions du système.

Le programme d'ensemble SCCOA, décomposé en étapes se succédant tous les 2 ou 3 ans, assure la mise en place ou la modernisation des systèmes dont a besoin l'Armée de l'air :

- une chaîne de commandement refondue qui intègre dans le CCOA les 3 composantes antérieures de la Défense aérienne, de la FATAC et du COTAM, en lien avec la nouvelle organisation de l'Armée de l'air,
- une composante mobile de fonctionnalités identiques aux centres fixes, le C3M,
- un STRIDA rénové, évoluant vers une architecture informatique modernisée et compatible avec la structure de type ACCS.

- un centre commun SCCOA/ACCS à Lyon Mont-Verdun.

Par rapport aux méthodes traditionnelles de gestion des moyens électroniques sol de l'Armée de l'air où les domaines de la détection, des télécommunications et de l'informatique étaient gérés de manière relativement autonome, le SCCOA constitue un effort méthodologique sans précédent pour analyser de manière systématique la cohérence d'ensemble entre les différentes opérations : cohérence opérationnelle, cohérence budgétaire, cohérence technique et calendaire.

Cet effort nous permet de développer un véritable schéma directeur qui a déjà été partiellement réalisé. Il nous permettra aussi de mieux maîtriser les coûts d'ensemble du système, y compris les coûts de maintien en condition opérationnelle. Cette méthode nous impose aussi de consacrer beaucoup plus de temps qu'auparavant à la définition précise du besoin et des spécifications techniques. Même si cette méthode semble devoir allonger les délais, dans la phase initiale, l'expérience montre que l'effort consenti au départ porte ses fruits au stade des essais d'intégration et de validation et que c'est bien en suivant une telle méthodologie qu'on a la meilleure chance de satisfaire au mieux les utilisateurs.

CREATION DU PROGRAMME

1989 : CREATION DU PROGRAMME

ARMEE DE L'AIR
EMAA / BSTI

DGA
DCAé / STTE

OFFICIER DE PROGRAMME SCCOA

DIRECTEUR DE PROGRAMME SCCOA

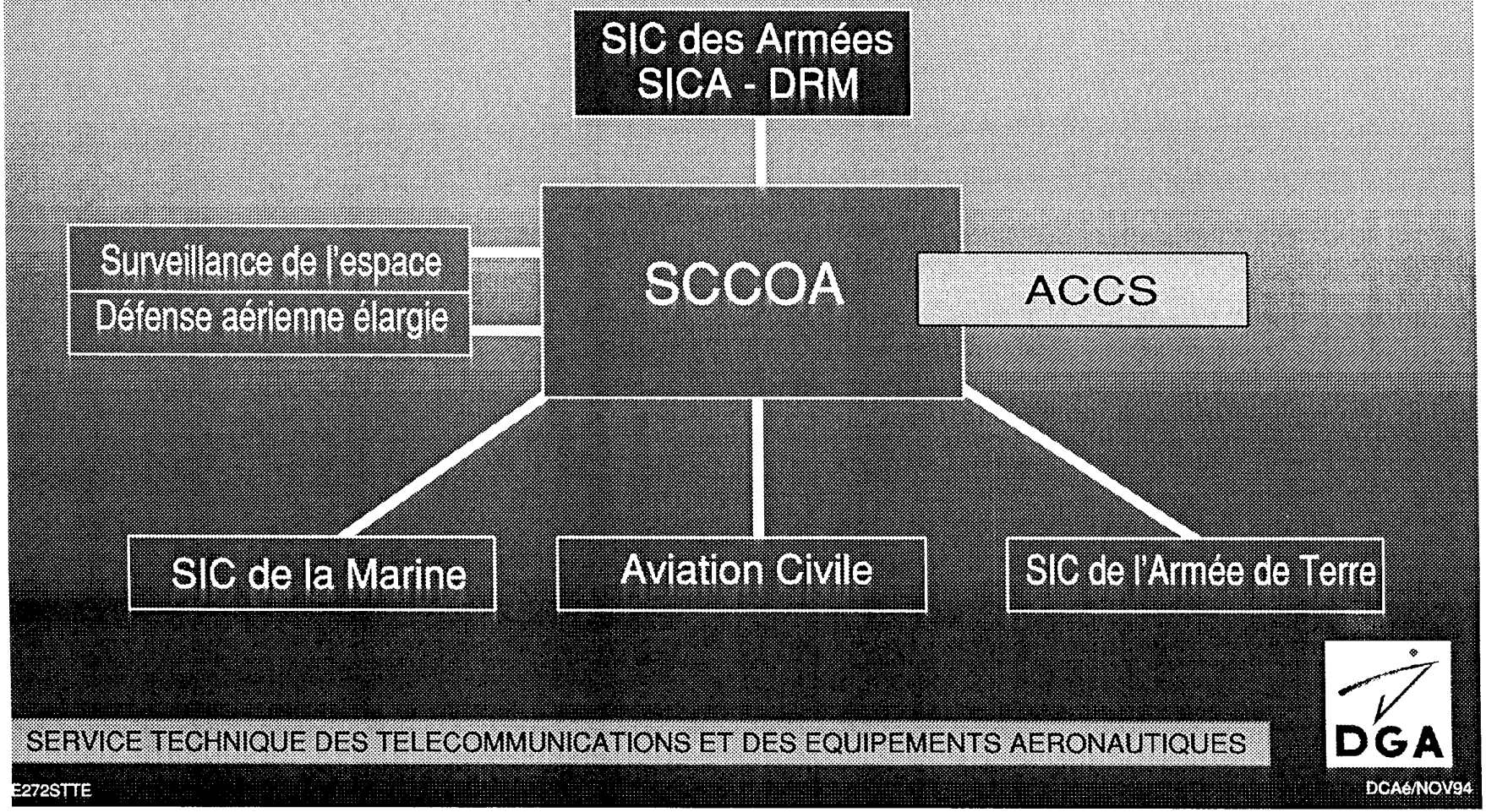
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LES INTERFACES



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LE PROGRAMME SCCOA

REGROUPE TOUS LES MOYENS DE COMMANDEMENT
ET DE CONTROLE DE L'ARMEE DE L'AIR
DANS UN PROGRAMME UNIQUE
AFIN DE MAITRISER LA CROISSANCE DE LA COMPLEXITE

- LOGICIELS DE PLUS EN PLUS GROS
- INTERFACES DE PLUS EN PLUS NOMBREUX
- DIFFICULTE DE LA PRISE EN COMPTE DE L'EXISTANT ET DE LA GESTION DES EVOLUTIONS

LES MOYENS DE DETECTION

- Radars de veille haute et moyenne altitude
  - 23 cm
    - PALMIER/ARES — 23 cm état solide
    - SATRAPE — TRS 22XX
    - TRS 2215 — OTH onde de ciel
    - TRS 22XX — RIAS
- Détection basse altitude
  - SDA (AWACS) — SDA (AWACS)
  - CENTAURE
  - ALADIN — Barrière HF
  - GUET A VE — OTH onde de surface
    Infrarouge, acoustique
- Défense aérienne élargie

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LES MOYENS DE TRANSMISSION

- RESEAUX SOL-AIR
  - METEOR
  - TELEAFFICHAGE
  - HAVE QUICK II
  - UHF DURCI
  - MIDS
  - NOEUDS SOL-AIR "ISARD"
- LIAISONS TACTIQUES
  - STRIDA-HAWK
  - SDCT-HAWK
  - COMPOSANTE TRANSMISSION DE LA CHAINE TACTIQUE (HQII - UHF - MIDS)
  - LIAISONS SDCT-CRC
- SOUS-SYSTEMES SOL
  - RESEAUX LOCAUX SCCOA

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E268STTE

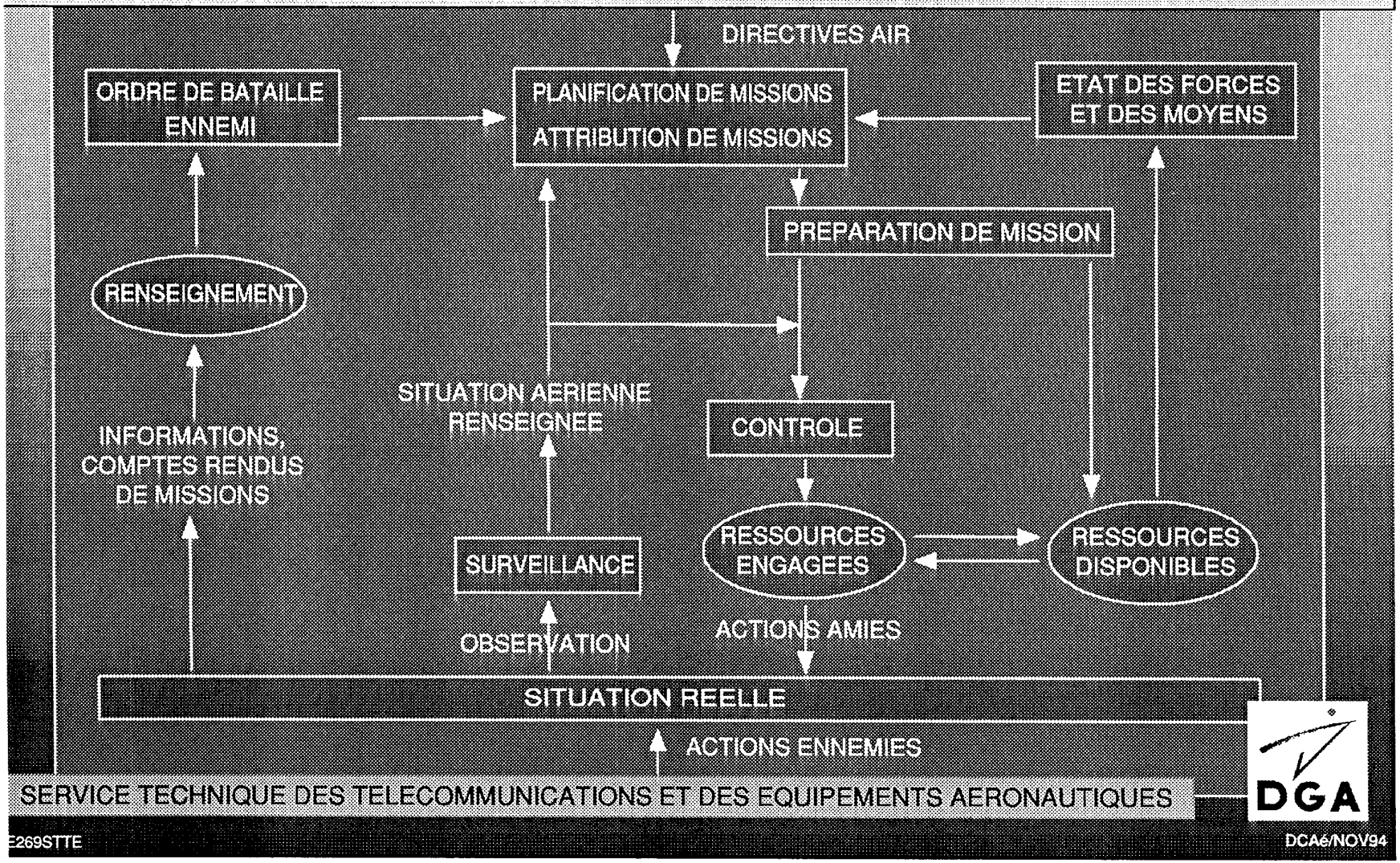
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LOGIQUE DE DEROULEMENT

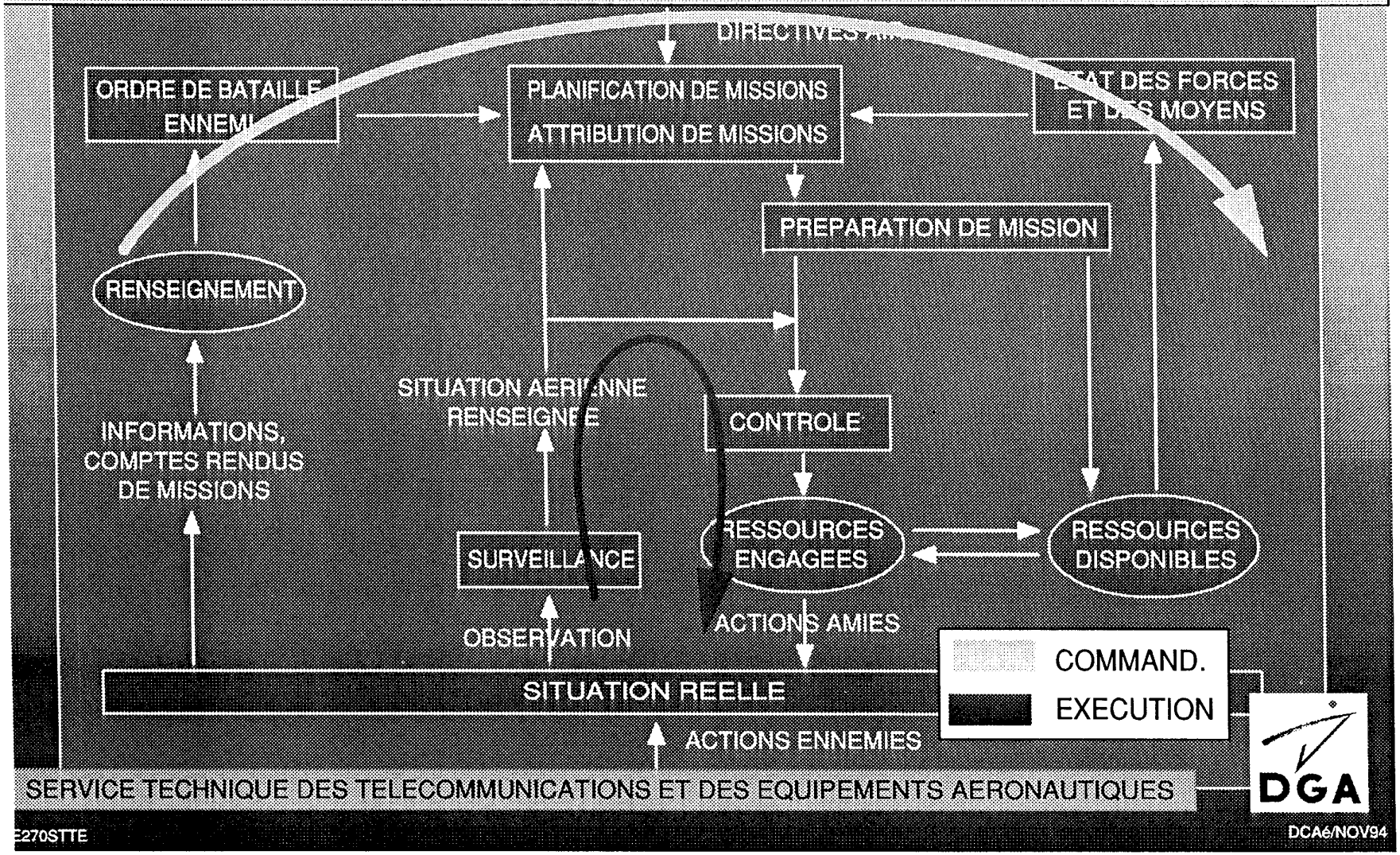
POUR CHAQUE CONSTITUANT :

PHASE A / B	PHASE C/D	PHASE E/F
FAISABILITE / DEFINITION	DEVELOPPEMENT / PRODUCTION	UTILISATION / RETRAIT DE SERVICE
OPERATION TECHNIQUE	**OPERATION TECHNIQUE**	**OPERATION TECHNIQUE**
ETUDE	REALISATION	MAINTIEN EN CONDITION OPERATIONNELLE

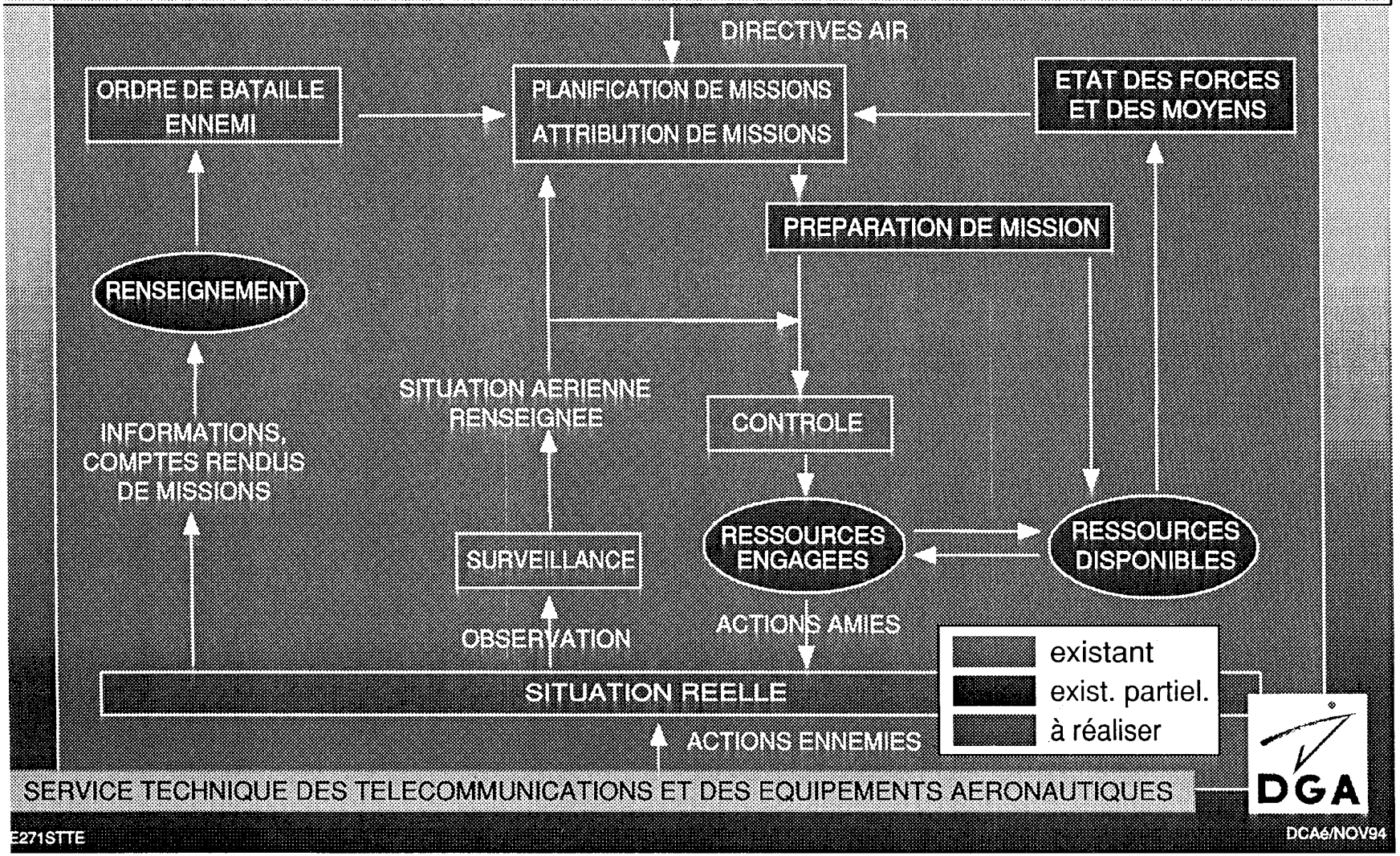
SYSTEMES D'INFORMATION ET DE COMMANDEMENT



SYSTEMES D'INFORMATION ET DE COMMANDEMENT



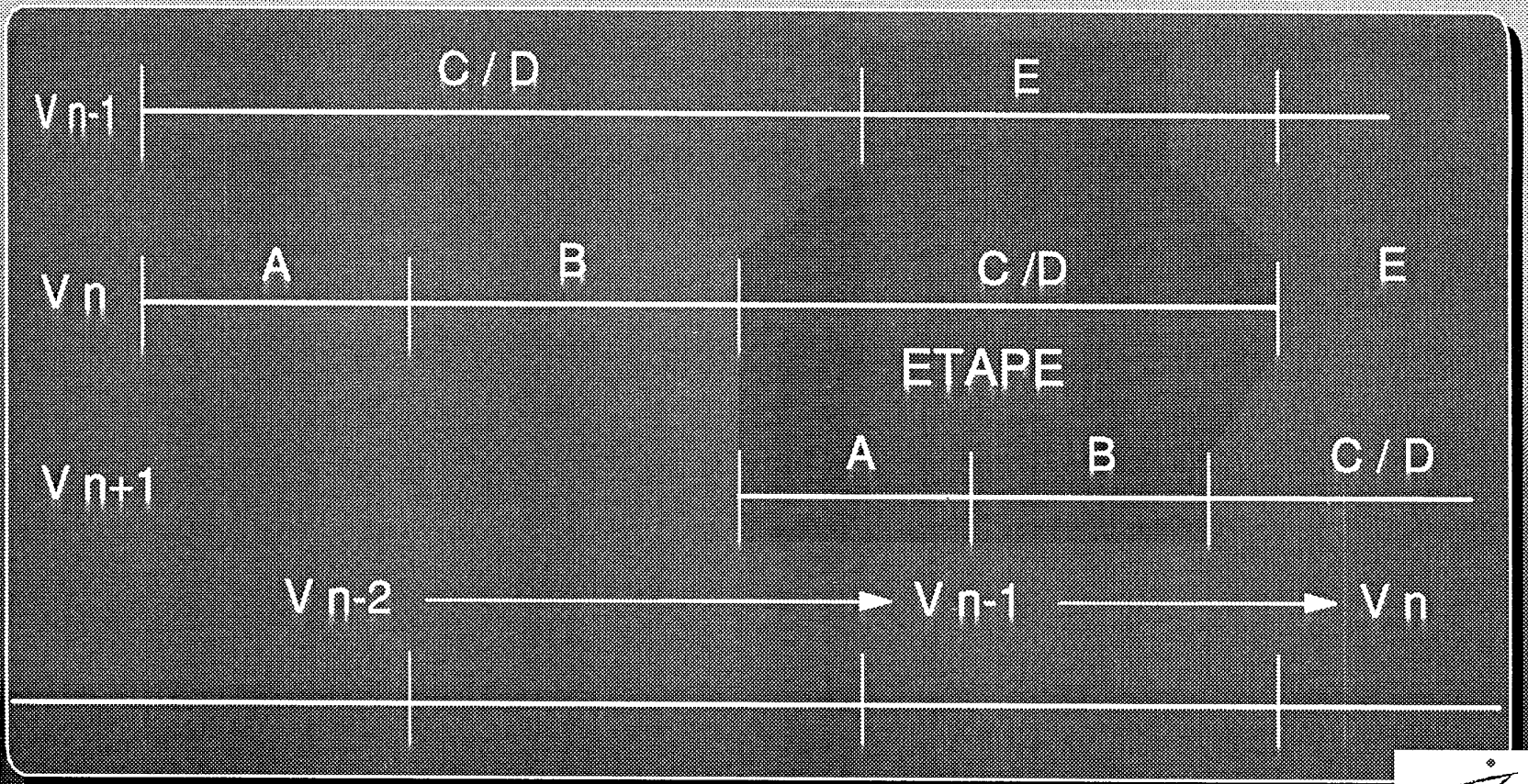
SYSTEMES D'INFORMATION ET DE COMMANDEMENT



LES GRANDS AXES

- FEDERER UN EXISTANT CONSIDERABLE
- FAIRE EVOLUER STRIDA
- STRUCTURER LES FONCTIONS DE COMMANDEMENT
- ASSURER L'INTEROPERABILITE ET LA COMPATIBILITE AVEC L'ACCS
- ACCOMPAGNER LA STRUCTURATION NOUVELLE DE L'ARMEE DE L'AIR
- DEVELOPPER LES FONCTIONS MOBILES

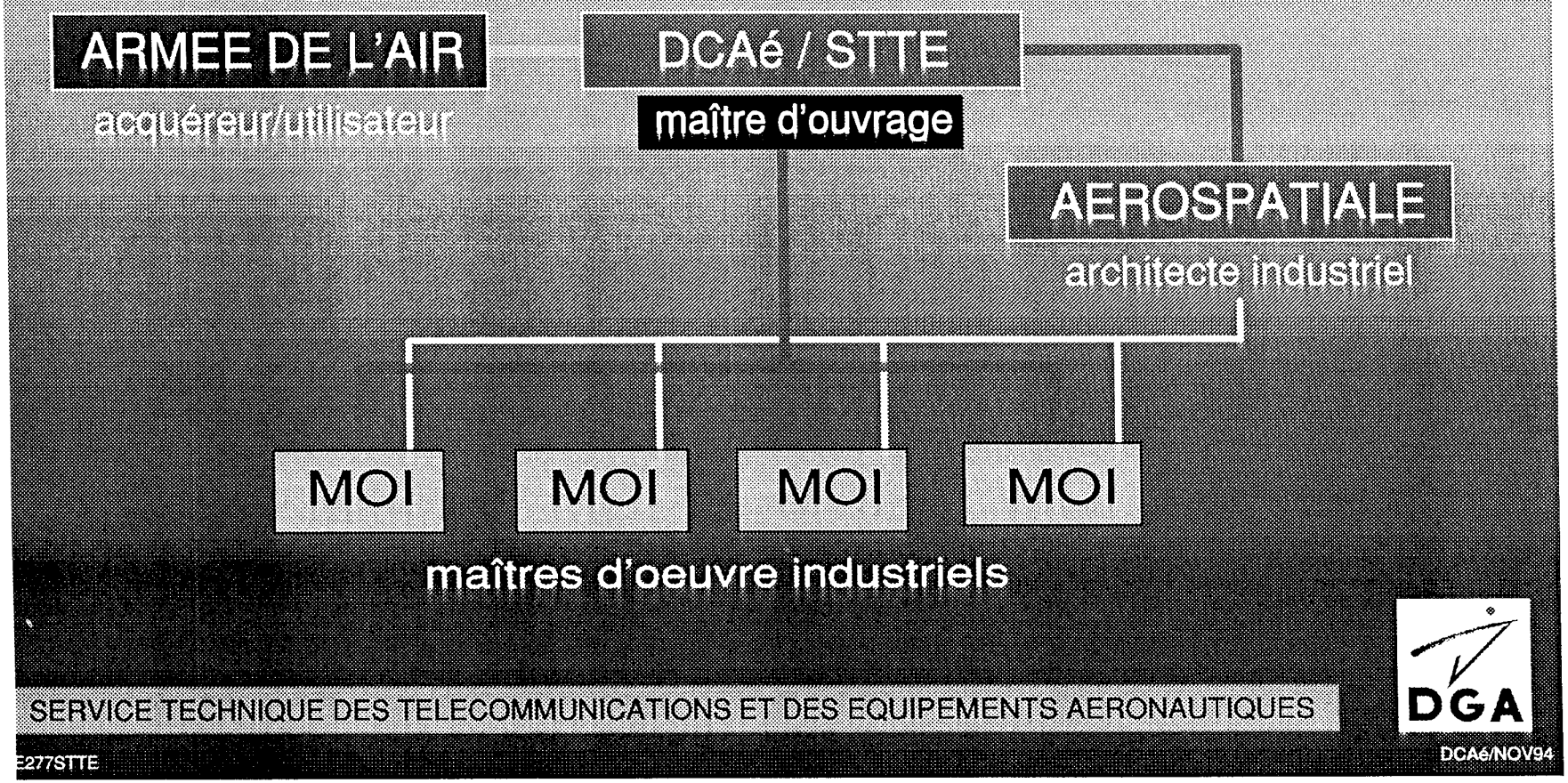
REALISATION DES VERSIONS



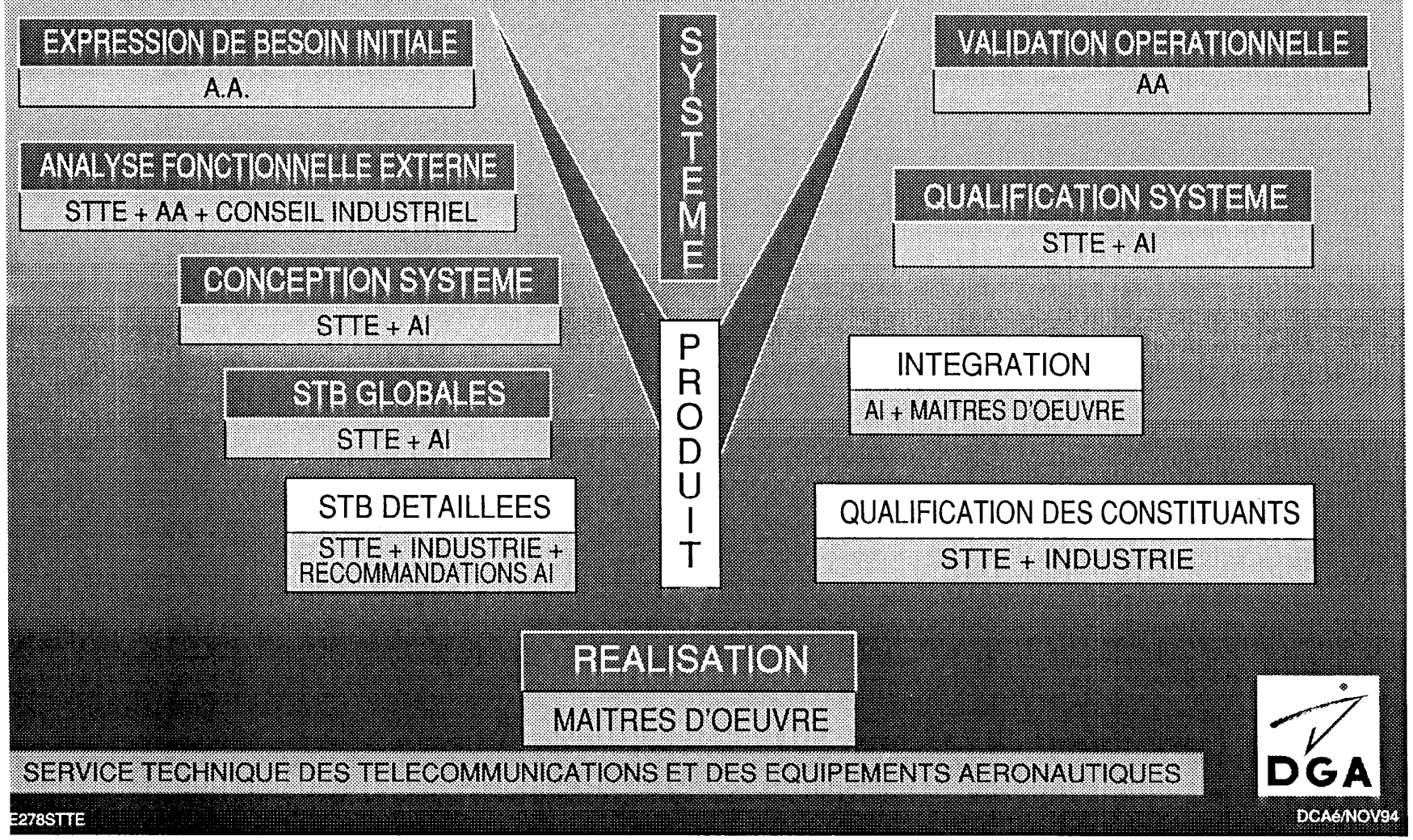
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ORGANISATION DU PROGRAMME SCCOA



ROLE DES PRINCIPAUX ACTEURS



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Aspects prospectifs des C3I Air

ICA Desnoës
Sous-directeur
DCAé — STTE
129, rue de la Convention
75731 Paris Cedex 15, France

Faire de la prospective c'est, d'une manière ou d'une autre, prédire l'avenir, et prédire l'avenir est toujours un exercice périlleux ; mais c'est un exercice indispensable dans un monde qui évolue rapidement, tout particulièrement dans le domaine de l'informatique, et donc des C3I. Mais comme il faut plusieurs lustres pour savoir de combien l'on a eu tort ou raison, le péril pour l'orateur n'est pas si grave.

En effet, nous devons nous situer ici à une échéance de dix à vingt ans, au-delà des périodes couvertes par les programmes dans leurs phases actuelles. Si l'on regarde les échelles de temps, on observe qu'il aura fallu de l'ordre d'une dizaine d'années pour mettre vraiment un programme comme le SCCOA sur rails à partir de l'idée initiale (qui date de 1986), et que les idées d'aujourd'hui mettront aussi une dizaine d'années pour faire leur chemin, et sans doute encore autant pour montrer leur réelle fécondité.

Je rappelle au passage que je n'exprime ici que des vues personnelles, que certains collègues m'ont aidé à préciser, mais qui n'engagent que moi.

1- **Avant de nous lancer dans des prédictions, il faut savoir comment nous interprétons les caractéristiques des systèmes actuels et comment nous les extrapolons vers le futur, s'il y a lieu d'extrapoler, car certaines caractéristiques, que je qualifierai d'invariants dynamiques, restent stables malgré la formidable évolution des technologies ; il s'agit notamment des diverses composantes de la croissance de la taille et de la complexité des systèmes.**

Première caractéristique : entraînés par la croissance des performances des matériels, les logiciels sont de plus en plus volumineux et contiennent un savoir-faire de plus en plus important, qui est en grande partie le savoir-faire de l'organisme utilisateur, lequel peut de moins en moins s'en passer. Ce sont donc des biens très précieux qui méritent des précautions extrêmes. Cela est encore plus vrai dans l'informatique dite de commandement qui est en quelque sorte une mise en conserve de concepts et de procédures opérationnels détaillés.

D'où une **deuxième caractéristique**, amplement confirmée par l'observation : les logiciels des grands systèmes informatiques évoluent beaucoup plus par retouches que par grandes refontes, car il faut coller à l'évolution des besoins, qui est rapide, sans remettre en cause l'acquis. Cette évolution des besoins est actuellement d'autant plus rapide que l'environnement vient de changer et que l'on sait mal se projeter dans le futur lointain. Si nous prenons l'exemple du STRIDA, qui vit depuis plus de trente ans à partir de la même base logicielle, nous observons qu'il doit s'adapter à l'évolution des capteurs, à celle des télécommunications, à celle de la gestion de l'espace et du contrôle du trafic par les civils, aux nouvelles liaisons tactiques comme la liaison 16, aux nouveaux aéronefs comme le Rafale, etc. C'est le progrès, et nous devons nous y associer. Cette évolutivité est notamment traduite dans la démarche dite PALP, ce qui signifie Programmes A Logiciel Prépondérant, démarche formalisée il y a quelques années par la DEI.

Troisième caractéristique, déduite de la précédente : la situation actuelle, où nous devons mettre en place beaucoup de systèmes C3I nouveaux, est exceptionnelle ; lorsque la plupart des fonctions auront été correctement informatisées, il ne s'agira plus en majorité que d'évolutions, c'est-à-dire d'adjonctions de compléments ou de modifications de petite taille par rapport à la base installée.

Quatrième caractéristique : l'un des enjeux majeurs est l'interopérabilité entre grands systèmes C3I, nationaux et alliés. Par exemple, le SICA, C3I des Etats-majors et centres d'opérations interarmées, doit être interopérable, entre autres, avec le SICF de l'Armée de terre, avec le SYCOM de la Marine, avec le SCCOA de l'Armée de l'air. Le SCCOA doit être interopérable avec l'ACCS, avec le SICA, avec le SICF, avec le SYCOM, avec MARTHA, avec SENIT, avec les systèmes d'armes divers, dont les avions de l'Armée de l'air, avec l'Aviation civile, etc. On peut ainsi identifier une trentaine de systèmes potentiellement en interface avec le SCCOA. Des systèmes de ce type continueront à exister, car le système de tous les systèmes serait ingérable et, vision personnelle, le restera dans le futur prévisible.

Cinquième caractéristique : les matériels et les logiciels de base se standardisent de plus en plus, ce qui contribue à la nécessaire pérennisation des logiciels mentionnée plus haut. Les standards les plus connus sont UNIX et ses dérivés comme POSIX. Les interfaces de communication se standardisent également, s'appuyant notamment sur le modèle OSI de l'ISO.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

Sixième caractéristique : on trouve sur le marché de plus en plus d'outils logiciels, que l'on peut encore appeler produits logiciels ou composants logiciels. Ces composants sont en général disponibles sur les grands standards du marché et permettent d'économiser sur le développement des applications et de bénéficier de services élaborés conçus par les meilleurs experts du domaine concerné, et ce sans disposer soi-même de l'expertise correspondante. Notons au passage que, là aussi, le logiciel contient un savoir-faire précieux et permet d'en faire bénéficier les utilisateurs, à condition bien sûr qu'ils reçoivent une formation adéquate.

Septième caractéristique : le génie logiciel s'appuie très peu sur les sciences exactes, non par ignorance des ingénieurs, mais parce que les niveaux de complexité atteints couramment dépassent largement nos capacités dans le domaine de la logique. Ma vision personnelle est que cela ne changera pas. Il ne faut donc pas attendre d'outil miracle qui résoudrait nos problèmes les plus épineux.

Huitième caractéristique : le moteur du progrès technique, notamment augmentation de capacité des machines, standardisation des logiciels de base et des produits divers, perfectionnement des méthodes, le moteur du progrès technique, disais-je, est surtout aujourd'hui dans le secteur civil.

Neuvième caractéristique fortement liée à la septième et à la huitième : le plus difficile n'est pas pour nous de faire évoluer la technique au sens strict, car nous trouvons maintenant beaucoup d'outils dans le secteur civil, le plus difficile, c'est de faire évoluer les hommes, leur mentalité, leur culture. Les vrais problèmes que nous rencontrons dans les C3I ne sont pas du domaine de la technique, mais de celui de l'organisation. Les systèmes C3I sont de plus en plus complexes et de plus en plus intégrés dans les processus de décision et de commandement ; leur maîtrise requiert une évolution des méthodes adaptée à celle de la technologie et de la complexité. Une mise en cause profonde des méthodes existantes sera probablement indispensable, ne serait-ce que par la nécessité de formaliser des processus de conception, de réalisation et de maintenance, processus qui auparavant étaient souvent peu formalisés. Il n'existe pas de méthode universelle que nous pourrions appliquer à la lettre à tous les cas concrets, comme l'illustrent les démarches de "plans qualité (au pluriel)" répondant à un "manuel qualité" ou de "plans de management (toujours au pluriel)" répondant à une "spécification de management" ; pour chaque projet, il faut particulariser la méthode à partir des principes généraux.

2- Ces prémisses étant posées, regardons maintenant, en nous appuyant sur les invariants que nous venons d'identifier, quelles conséquences nous pouvons en tirer pour le moyen et le long terme.

Tout d'abord, nous pouvons parier presque à coup sûr que la taille des logiciels des C3I continuera à augmenter, entraînant la croissance corrélative de leur complexité. La question est de savoir jusqu'où croîtra cette taille. Comme les systèmes d'armes sont eux-mêmes de plus en plus complexes, et comme les C3I leur sont indispensables et participent eux-mêmes à la lutte entre l'obus et la cuirasse, il est probable que la plupart de ces C3I vont croître jusqu'à la taille maximale maîtrisable, ce qui devrait leur donner l'efficacité maximale.

Certains diront que, si l'on a du mal à réaliser quelques gros systèmes, il n'y a qu'à en réaliser beaucoup de petits. Cela est praticable si ces petits systèmes sont indépendants. Un ensemble de petits systèmes fortement dépendants les uns des autres sera beaucoup plus difficile à coordonner qu'un grand système exécutant les mêmes fonctions, et présentera de plus le risque que chaque petit système tende vers la taille logicielle maximale et qu'une partie importante du logiciel soit consacrée à la gestion des incohérences inévitables entre développements séparés. On voit donc que, si l'on veut limiter la taille globale, et donc le coût global, on a intérêt à regrouper les systèmes fortement corrélés.

L'optimum n'est pas aisé à définir, et sa définition n'est pas aisée à objectiver, mais l'on sent là un ensemble de forces qui poussent à retenir de gros systèmes en nombre relativement restreint, qui auront une tendance naturelle à devenir les plus gros possible, dans les limites de l'efficacité. Le contour de ces systèmes doit être défini en priorité en fonction des interactions entre les fonctions concernées, donc en fonction du besoin opérationnel.

Deuxième tendance : la qualité des logiciels au sens large, en y incluant selon un usage assez répandu les aspects sécurité, fiabilité, flexibilité, maintenabilité, etc., cette qualité, donc, va devenir un élément primordial de tous les programmes C3I (et de beaucoup d'autres également, mais là n'est pas notre propos). En effet, comme nous l'avons vu, le logiciel va contenir une quantité de savoir-faire opérationnel de plus en plus importante, savoir-faire qu'il sera de plus en plus impraticable de régénérer complètement lors d'une rénovation.

On peut certes arguer que l'industrie, qui réalise la plupart des systèmes, pourrait s'arranger seule de cet aspect des choses. Cela sera insuffisant pour deux raisons au moins :

- premièrement, on imagine difficilement que la visibilité sur l'un des biens les plus précieux d'une organisation, son logiciel, soit entièrement déléguée à l'industrie,
- deuxièmement, la qualité se décline en un certain nombre de critères qui ne sont pas définissables dans l'absolu, mais qu'il faut au contraire préciser pour chaque système, et faire vivre comme des spécifications, dont ils font d'ailleurs partie. Cela nécessite une participation étroite des opérationnels.

Troisième tendance : les composants logiciels vont se généraliser aussi dans le domaine C3I. Je veux dire ici que nous allons voir se multiplier des outils logiciels du type de ceux que nous trouvons aujourd'hui dans le commerce civil, mais pour des fonctions typiquement militaires. Pour illustrer mon propos, je citerai pour le civil des systèmes de gestion des bases de données, des gestionnaires d'écrans, des tableurs, des traitements de texte, des progiciels de comptabilité, etc. Dans le domaine des C3I AIR, il n'y a pas grand chose à citer aujourd'hui, mais la technologie existe, mais les matériels et logiciels de base se standardisent, et l'on voit immédiatement l'intérêt pour l'interopérabilité de bâtir des systèmes différents à partir de modules communs. On peut imaginer, par exemple, des composants logiciels pour s'abonner aux liaisons tactiques normalisées, pour gérer des données géographiques, pour contrôler des systèmes d'armes, pour proposer des décisions, pour formater des messages, etc.

Remarquons également que c'est un excellent moyen de faire baisser la complexité d'ensemble.

C'est déjà comme cela que procède peu ou prou l'industrie de défense, mais chaque société conserve jalousement l'exclusivité de ses composants.

Imaginons une situation où, comme cela se généralise dans le secteur civil, chacun pourrait bénéficier du meilleur composant, sur lequel la loi du marché concentrerait l'investissement : il est clair que l'efficacité globale en serait nettement augmentée, et que chacun en tirerait des avantages substantiels à condition de savoir se créer des pôles d'excellence et de savoir les conserver. Dans un domaine dépendant fortement de l'action et de l'investissement étatiques, la tendance paraît inéluctable, et il vaut mieux s'y préparer le plus tôt possible.

Dans ce que je viens de dire, je souligne l'importance, à mes yeux, de "la loi du marché". Je pense que, pour des composants utilisables dans de multiples systèmes, il faudrait se garder d'imposer systématiquement à l'industrie des bibliothèques de composants standardisés développés à l'économie sous l'autorité de l'Etat, avec notamment un seul composant par fonction, car le risque de décalage par rapport à l'environnement international serait trop grand. La bonne démarche est sans doute de rassembler un maximum de composants dans des bibliothèques ou des catalogues communs, avec accès au marché international, et de laisser les responsables de projets faire leur meilleur choix en fonction des exigences qui leur sont imposées. Pour les composants utilisés dans un seul système, ou dans un petit nombre d'entre eux, l'unicité sera par contre beaucoup plus fréquente.

Tout cela, bien sûr, ne sera possible que grâce à la poursuite de la standardisation des architectures, des logiciels de base et des interfaces, standardisation à laquelle les composants logiciels contribueront également. On peut d'ailleurs anticiper que, dans certains cas, l'interface entre applications sera formalisée par des composants logiciels communs et non plus par des spécifications communes au sens où nous l'entendons aujourd'hui : on fera ainsi l'économie de développements multiples pour des fonctions voisines, et surtout l'on éliminera les tests de cohérence entre logiciels développés à partir de spécifications communes, ainsi d'ailleurs que les incohérences résiduelles, qu'il est pratiquement impossible d'éliminer.

Trois remarques encore avant de quitter ce sujet, visant plus particulièrement les aspects industriels :

- tout d'abord, les dispositifs techniques et juridiques permettant de protéger le savoir-faire sur ce type de marché existent,
- deuxièmement, la valeur ajoutée sur la vente d'un système concerne en majorité les développements nouveaux et peu la vente des composants logiciels. Il n'y a donc pas de réel manque à gagner à utiliser des composants développés par un autre.
- considérée globalement, l'industrie a intérêt à voir l'investissement étatique se concentrer sur des développements innovants plutôt que sur le financement de doublons inutiles.

Quatrième tendance : il faudra que nous améliorions à la fois la rapidité de conception des C3I et la rigueur des réalisations. En effet, beaucoup des systèmes actuels se retrouvent décalés par rapport au besoin lorsqu'ils sont mis en service, car d'une part l'on a du mal à bien formaliser ce que l'on attend d'un système complexe futur et, d'autre part, il est parfois difficile de prévoir le besoin longtemps à l'avance. Le phénomène est aggravé par la croissance de la taille des systèmes qui tend à rendre les modifications plus difficiles, donc plus longues à mettre en oeuvre. Des outils de maquettage de plus en plus puissants permettront de concevoir rapidement de nouvelles fonctions en se basant sur le système réel ou sur une simulation fine de celui-ci, ce que l'on pourrait appeler "maquettage évolutif". Ces maquettes pourront dans certains cas être utilisées opérationnellement. Mais il sera impératif d'intégrer les fonctions correspondantes dans un processus rigoureux de réalisation, dans le cadre d'une ingénierie de systèmes formalisée. Cela permettra de mieux prévoir le besoin détaillé et de mieux le préciser, et ce le plus tard possible, de manière à limiter les décalages précités entre besoin et réalisation. Vouloir faire l'économie de la rigueur serait à terme la certitude de se noyer dans la complexité et de perdre une partie importante du savoir-faire contenu dans les logiciels.

Cinquième tendance : on devrait assister à un développement notable des équipes d'officiers de haut niveau spécialisées dans la conception et l'utilisation des C3I, en y incluant la doctrine et les procédures d'emploi.

Les armées de l'air ne peuvent se désintéresser des logiciels qui leur sont indispensables et qui contiendront une part de plus en plus importante de leur savoir-faire opérationnel, et doivent d'ailleurs, avant d'en arriver là, consacrer des effectifs significatifs à la conception de ces logiciels. L'effort d'abstraction et de structuration nécessaire pour concevoir des composants pérennes doit débuter dans le domaine de l'utilisation opérationnelle et devra s'y référer en permanence.

Sixième tendance : l'ingénierie du logiciel deviendra de plus en plus une science à part entière, et les C3I devraient y jouer un rôle particulièrement moteur.

Science à part entière : aujourd'hui, on a trop tendance à considérer que l'ingénierie du logiciel est identique à celle des autres systèmes, ou même qu'il suffit d'assembler des produits existants sans formalisation de l'ingénierie. Cela est inadéquat pour la maîtrise des différentes caractéristiques que nous avons observées jusqu'à présent. Les grands systèmes informatiques sont des objets particuliers, auxquels la méthode scientifique doit aussi être appliquée, et ce d'autant plus qu'ils sont particulièrement difficiles à formaliser.

Rôle moteur des C3I : que l'on me permette ici d'être un peu chauvin. Les informations manipulées par les militaires sont beaucoup plus nombreuses et plus complexes que celles qui son manipulées par les civils, et ces informations se situent dans des environnements potentiellement beaucoup plus hostiles, avec des délais de réaction beaucoup plus courts et en interopérabilité beaucoup plus étroite avec des partenaires beaucoup plus nombreux. Un grand SIC, c'est un peu comme si l'on intégrait dans une entreprise les systèmes de gestion des stocks, de comptabilité générale, de comptabilité analytique, d'ateliers automatiques, d'information sur la concurrence, etc., le tout en temps réel et en interopérabilité totale avec les fournisseurs, les clients et les banquiers. On en est encore très loin, et c'est sans doute l'une des raisons pour lesquelles les outils et méthodes du secteur civil dit "de la gestion" sont assez peu appliqués à nos C3I. Il y a certainement des progrès à faire en s'en inspirant plus, mais cela ne suffira pas pour satisfaire l'ensemble du besoin. Les C3I devront se préoccuper eux-mêmes de l'application du savoir-faire existant à leur domaine, et devront pour cela y apporter des améliorations significatives.

Septième tendance : les organisations de commandement deviennent de plus en plus évolutives, d'où il découle deux conséquences :

- les systèmes doivent être très flexibles ; la structure de commandement peut évoluer rapidement, mais les fonctions restent de par leur nature relativement stables,
- il est en conséquence indispensable que les systèmes C3I soient conçus à partir de leurs aspects fonctionnels et non à partir des structures des commandements ou des centres d'opérations.

Par exemple, les fonctions AIR doivent former un tout cohérent parce que, comme le Général Douin nous l'a rappelé, la bataille aérienne est et restera unique sur un théâtre d'opérations donné.

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Il serait hasardeux d'aller plus avant aujourd'hui dans cette vision du futur. J'espère que certains l'ont trouvée un peu dépassée et que d'autres l'ont trouvée plutôt idéale, car cela prouverait qu'elle aurait atteint le juste compromis permettant de susciter la réflexion, sans prétendre à l'exactitude, qui n'existe pas à si long terme. Et c'est justement de compromis qu'il s'agit dans notre démarche d'amélioration permanente de maîtrise des C3I : compromis entre rigueur et rapidité, compromis entre formalisme et empirisme, compromis entre concurrence et coopération, compromis entre étatique et industriel, et nous pourrions allonger à volonté la liste des compromis à faire évoluer entre les diverses forces en présence. Dans ce mouvement, qui est celui de tous les grands systèmes informatiques, les C3I devraient jouer un rôle moteur, ce que reflète particulièrement l'organisation spécifique mise en place sous l'égide de l'Etat-major des armées et de la Direction de l'électronique et de l'informatique de la DGA.

Dans ce contexte, les C3I AIR, et notamment le SCCOA, devraient se placer particulièrement en pointe, car c'est dans notre secteur que le besoin de cohérence à grande échelle est le plus fort, ce qui explique d'ailleurs la création du programme SCCOA. Les opérations aériennes sont conduites à partir d'organismes centralisés, dans un espace aérien unique, à partir de bases qui doivent être capables d'accueillir tous les types d'avions, avec des délais de réaction extrêmement courts et en interopérabilité permanente avec nos alliés.

Soyons ambitieux et espérons que les progrès nécessaires pour la maîtrise de ces systèmes complexes nous rendront, au moins partiellement, le leadership que nous avons perdu au profit du secteur civil.

Air Force C3I Architecture Concepts

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1. THE ARCHITECTURE ISSUE

Architecture: a word that is used in more and more areas and namely in the C3I world. What is an architecture, who is the architect and what is his business, what are the relationships with the other players, what are his tools and how does he work? This is the purpose of this briefing.

An architecture concept applies to a system, the complexity of which is more than simply the **addition** or the **connexion** of subsystems. This is the way large C3I systems for Air Defense and Air Operations can be designed, since they are federating a large set of planning, tasking, mission preparation, mission control, intelligence, communications that are overlapping in a complex set of System of Systems.

This intrication of the missions and functions in a Combined, Joint environment has generated the need for a separation between **organic** and **operational** functions: in France, a single operational command, the CDAOA (Air Defense and Air Operations Command) has authority and responsibility for the organization, command and control of any mission of the French Air Force, let it be defensive, offensive or support, either in a national environment, or in coordination with the Allies.

Combined joint operations have push to more coordinated C3I systems: the NATO ACCS and the french SCCOA (Système de Commandement et de Conduite des Opérations Aériennes) are the most obvious examples. Furthermore, the top-down requirements for a comprehensive Command and Control system is complemented by the bottom-up pressure from technology: Commercial off-the-shelf products, national standards and procedures, worldwide integration of communication systems make a coordination necessary at system of systems level. That is the work of an Architect.

2. THE SCCOA ENVIRONMENT

The SCCOA environment demonstrates how complex the interfaces are; and the interfaces do not only transfer data and bytes: they have to be described first as common doctrines and procedures between neighboring systems.

- As far as ACCS is concerned, the interface with SCCOA is more than a border: both systems are developed in parallel, according to similar standards, and according to a similar functional breakdown; an ACCS Command and Control Center, the CARS in Lyon-Montverdun, will be implemented in France.
- As far as Air Traffic Control and Air Traffic Management is concerned, the regulations and procedures must be shared and coordinated between the civilian and the military. In France, the military air traffic management is fully independent from the civilian, and the sharing of responsibilities is varying according to peace, crisis and war situation.
- Joint operations require coordination and integration. An example is the development of a joint mission preparation system for the Air Force and for the aircraft carriers and the airbases of the French Navy Aviation.
- At joint Chief of Staff level, the frame of national intelligence (the DRM for Direction du Renseignement Militaire) must be coordinated with the Air Intelligence, which produces intelligence data from the Air Force sensors, and which processes and uses intelligence data for the Air Operations.

All these relations and interfaces have to be organized and managed. This is not a self generated process.

3. THE NEW FUNCTIONS IN SCCOA

SCCOA develops and implements new concepts within the Air Force structure:

- the Air Command and Control process is suited to the new Air Force organization that was implemented in June, 1994: a single operational Command is in charge of defensive, offensive and support operations; it relies on the main national Command Center for Air Operations (CCOA) in Taverny near Paris. The common ACCS/SCCOA center of Lyon-Montverdun will later be closely integrated in the planning tasking and mission control process.
- a mobile, air transportable Command and Control system (the C3M) will be developed for overseas operations. It will perform the planning and tasking functions, and the air mission control and air traffic control as well.
- new communication networks will integrate Link 16,
- finally, the air operations will be organized as an Extended Air Defense concept, as defined in the White Paper on defense released in spring 1994.

SCCOA is in charge of the development and integration of these new functions along with the evolution of the former systems, namely STRIDA.

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4. ARCHITECT AND PRIME CONTRACTORS

The spectrum and the complexity of a such system as SCCOA requires a System Engineering organization. As far as C3I systems are concerned, system engineering supports both **operational** and **technical** functions, along with tools and methods for the management of a very large programme. Stand-alone systems drive more or less a single prime contractor structure. Large, distributed C3I systems are rather a federation of subsystems that must work all together in a smooth and flexible way.

In the USA, the word "Architect" is more or less equivalent to a "System Engineering and Integration" (SEI) contract. It goes along with a software and hardware exclusion clause to prevent any conflict of interest between the SEI organization and the contractors of the subsets of the system.
Due to the design and overall structure of SCCOA, this SEI activity looks rather like a System of Systems Engineering (SSE) contract.

5. THE PLAYERS

Starting from the well known V-like process for the development of a system, we can define three main players:

- the Air Force, in charge of the statement of the operational requirements, at the upper left of the process,
- the Architect, on behalf of the Government Agency (DCAe/STTE) in charge of the system management and system engineering, in the central part of the V. The main output of the Architect are the general specifications, at System and Subsystem levels. These specifications are the input for the subsystem developers.
- the subsystem developers, at the bottom of the V. They develop hardware and software according to the general specifications derived by the Architect. They get their development contracts from the Government Agency (STTE), not from the Architect. Therefore, their is no overall prime contractor in the process.

After completion of the development, the subsystems acceptance tests are performed; then, a validation at system level is carried out in a System Test Bed (the Centre de Définition, Expérimentation et Validation du SCCOA, or CDEVS) located on the Air Force Test Base of Mont de Marsan. The equipments are assembled and integrated in a system level configuration, linked to real world systems like radars, AWACS, SAMS, CRCS, etc., and check-out of overall system performance is carried out.

In this process, the Architect is in charge of the consistency of the full system, industry contractors being in charge of the development of the elements.

6. THE SYSTEM BREAKDOWN

The system breakdown derives from two processes:

- the operational requirements statement from the Air Force, though a long and tedious functional analysis process,
- the development of a functional architecture that translates the operational structure into building blocks and helps deriving the data flows and processing power required.

SCCOA is built around the same functional architecture as the ACCS, though the physical implementation may be very different due to the specific organization of the french Air Force. Besides, the spectrum of SCCOA is larger than the ACCS, since SCCOA encompasses more functions (especially Intelligence and higher level Commands that are embedded in the ACE-ACCIS or BICES programmes in the NATO structure).

The physical architecture is based upon **equipments** implemented in various **centers**: for example, the equipments dedicated to Force Management are scattered in the CCOA, the Wing Operation Centers, the Squadron Operation Centers, etc.

7. SYSTEM MANAGEMENT

SCCOA has demonstrated that large C3I systems must stress some key management issues:

- the derivation of the military requirements,
- the need for a common system engineering activity between the Air Force (the user), the Government Agency (responsible for the development) and the industry (Architect and contractors). C3I systems need an iterative and flexible roadmap because of:
  - the man-in-the-loop who influences the derivation of the requirements, compared to more automated systems,
  - the rapid evolution of the hardware and software products and namely the COTS (Commercial-off-the-shelf) that make obsolete rigid, stiff systems compared to layered, flexible, open designs.

Rapid prototyping, demonstration/validation labs are keys to the implementation of systems that the user may play with very early, and can make evolve as soon and as frequently as he needs.

The Test Bed, at system level, is the place where ultimate validation and doctrine or procedure evolution may be controlled.

8. THE ARCHITECT TOOLS

The Architect relies on several tools to perform system management and system engineering:

- the management specification is the common law of the players. It defines the management principles, the breakdown organization, the relationship and responsibility of the players. It is written so as to allow the contractors to respond to the requirements according to their own culture and to their general tools, provided they are compliant with the overall requirements.
- the System Studies encompass top-down analysis (architecture analysis, input/output and interface requirements, flow analysis, etc.) and cross-system requirements (safety, reliability, LSI, etc.). They assess the system consistency and the system breakdown.
- the System Planning and System guidelines is a schedule, a budget plan and a consistency matrix between subsystems. It runs over a 12 years time frame.
- the System Test Bed (CDEVS).

CONCLUSION

SCCOA is a major programme, part of the french Military Programmes Law. It develops and federates numerous systems that support the new organization of the French Air Force, based upon a single Operational Command.

The development is structured according to phases, each of them running over a few years, and overlapping: each phase develops new elements, and prepares for the development of future ones in the next phase.

This process is made mandatory because the evolution of the operational requirements and of the technology is not predictable over a very long period. Therefore, a flexible organization has to be set up, but the more flexible it is, the more coordination it requires. Defining long term planning, smoothing the budget, making consistent the requirements, mixing existing systems and brand new ones, making possible combined joint operations is the mission of the System Architect, on behalf of the Air Force and of the DGA, with the support of the industry contractors.

A Technical Management Structure for the Evolution of Tactical Aerospace C³I Systems

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1. SUMMARY

A technical management structure using Model-Based Systems Engineering (MBSE) concepts and implemented via an integrated suite of tools is recommended to manage the evolution of tactical aerospace C³I systems. A system-of-systems (S2) engineering perspective is advocated to identify processes, methods, and tools that support the capture, analysis, and management of these systems. An integrated systems engineering environment (ISEE) is introduced as the mechanism used to capture, store, and generate the information necessary to manage change across tactical aerospace C³I systems.

Work currently being performed to manage change of the Air Warning Mission C³I systems within the Integrated Tactical Warning/Attack Assessment (Integrated TW/AA) S2 is discussed to show how MBSE concepts are currently being used. Extensions of this work are presented in terms of an evolving tactical aerospace C³I systems architecture and the inclusion of other tools. Finally, advances in enabling technologies, methods, and tools are mentioned to suggest directions of how to fully develop a tactical aerospace C³I systems ISEE.

2. INTRODUCTION

Lifecycle change management of the multinational tactical aerospace C³I S2 is a complex engineering management effort that is expected to continue. In [1], a proposed architecture for future tactical air operations C⁴I is discussed. The complexities of understanding the behavior of such an architecture, along with the migration of today's primarily "stovepiped" systems to achieve an interoperable architecture, are considered a major technical and management challenge. The disciplined approach of MBSE, when coupled with an ISEE comprised of commercial-off-the-shelf (COTS) tools, appears to be a promising systems engineering (SE) approach to help manage such an evolution.

2.1 Model-Based Systems Engineering

In [2, 3], MBSE is described as the discipline required of SE to design and build a real system based on a thorough and rigorous understanding of all requirements. Such an understanding is necessary to create a model that will yield the design of the system. From this design, a real system can then be built that will satisfy all of its requirements. This formal approach to SE, one built upon the use of models to design the system, is extended here and applied throughout a system's lifecycle. These MBSE tenets are subscribed to here to investigate how models built using COTS tools can support the lifecycle changes of the tactical aerospace C³I S2. The lifecycle phases, as described within MBSE, are:

1. Requirements development
2. Concept development
3. Full-scale engineering development
4. System development
5. System test and integration
6. System operation
7. System retirement

Change management of the tactical aerospace C³I S2 is concerned with each lifecycle phase of all systems, along with that of the integrated S2. Hence, the view taken is one of managing the evolution of the S2 through knowledge of each C³I system and its end-to-end behavior. In addition, different architectural configurations demand that change management be supported via differing views of the design. That is, the design capture and display methods must be sufficiently robust to support multiple views of the S2 [4]. This allows engineers and managers to view, analyze, assess, and document the evolution of the S2 from the most useful perspective that meets their needs.

Figure 1 shows a simple MBSE "process" engine that depicts the major steps that must be performed in each phase of the lifecycle [5]. Each step represents a set of tasks that is tailored to meet the specific goals within each lifecycle phase. In addition, this iterative process is applicable at any level of detail within each phase. Hence, this tailorable and iterative model can be repeatedly applied across the seven lifecycle phases, as well as throughout each layer of detail. Models constructed in one phase will evolve as the system progresses through its lifecycle.

The Behavior Model in Figure 1 refers to "what the system or S2 does," while the Object Model captures "how the system or S2 is implemented." Here, "object" refers to real-world objects (e.g., bioware, hardware, and software). Under Trade-Off Analysis, issues involving performance vs. cost, programmatics vs. cost, technology vs. risk, etc., are examined. Once a feasible solution is achieved, the Build-and-Test Plan based on the models is then created.

The use of models to design systems and control system change differs from today's predominant approach of using documents to drive the design. Although documentation is extremely important and useful, document-driven design and its subsequent use to manage the evolution of a system has often proven itself inadequate. Such inadequacies stem

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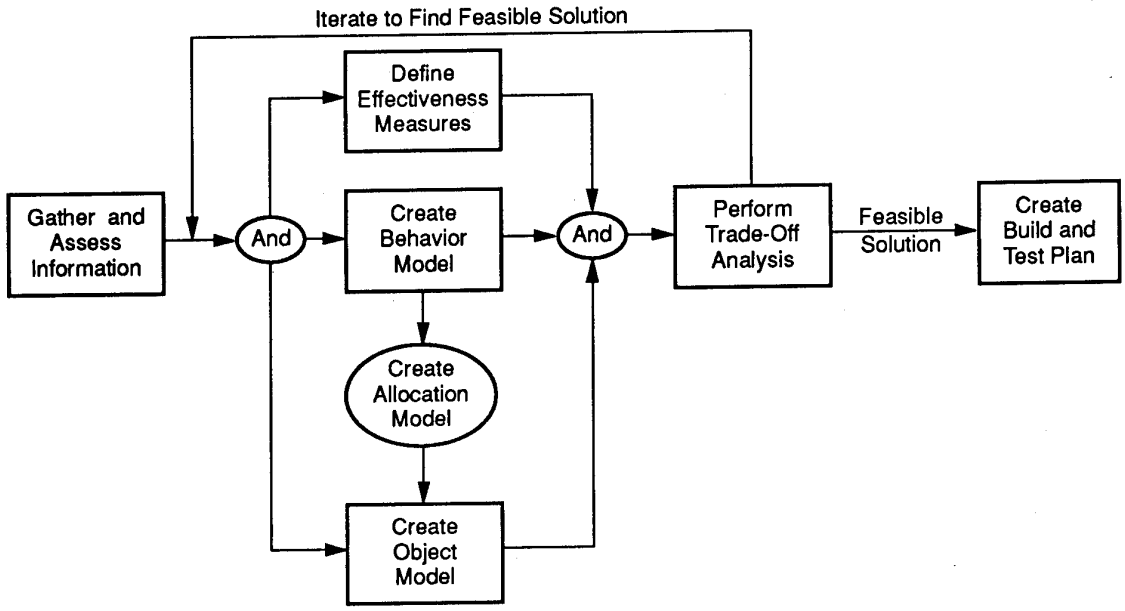


Figure 1. Model-Based Systems Engineering "Process"

from such things as the informality and inexactness of the written language and the inability to maintain the voluminous documentation required by today's acquisition processes [6]. MBSE offers a formal approach that, when coupled with an ISEE, permits the generation of documentation in any desired format.

The overall goal is to satisfy all requirements via models. The model-captured information is then used to provide customized documents that address specific customer needs and/or technical and management issues. This approach is used in [7, 8], where COTS tools are used to capture C^3I S2 architectures, as well as to produce useful documents.

To be successful in the design and evolution of complex S2, MBSE requires an implementation vehicle beyond paper and pencil. The emergence of COTS SE tools, the existence of several domain-specific COTS tools, and the appearance of standards-based COTS products that provide the underlying technology, all contribute to the realization of an implementable MBSE approach. The next section discusses the expanded role of tools in the 21st century as they apply to the tactical aerospace C^3I S2 arena.

2.2 Expected Roles of SE Tools

SE tools are expected to support the entire lifecycle of a system, expanding their focus to include the entire design capture process [4]. The following lists some of the more important types of information that are expected to be captured by tools-developed models within each phase of the lifecycle:

1. Requirements Development
   - External environment context
   - "What if?" scenarios (new threats, missions, technology, etc.)
   - End user requirements traceability
   - Risk assessment
   - Effectiveness measures

2.-4. Concept Development, Full-Scale Engineering Development, System Development
   - System architecture (functional, physical, operational views)
   - Architecture mapping to requirements, effectiveness measures
   - Specification generation
   - History of decision making, rationale, trade-offs
   - Design strategies, implementations
   - Interface definitions
   - Capture of data items and messages across internal/external interfaces
   - Information on standards, protocols, and products
   - Traceability to requirements and documentation
   - Interoperability and integration analyses

5. System Test and Integration
   - Traceability at all levels to objects, requirements, system effectiveness measures, and documentation
   - Test plans and procedures, exit criteria
   - Historical record of results, problems, outstanding issues, modifications, etc.

6. System Operation
   - Record of "what if?" exploration analyses and upgrades

- Cost and re-engineering data
- Requirements changes
- External/internal drivers, resulting changes, and data on the decision process
- COTS product migrations

7. System Retirement
   - Environmental considerations
   - Disposal facilities information

Achieving these expectations for systems of the scale of the tactical aerospace C^3I S2 requires a set of large, complex models. The capability of tools to scale up to address such a class of problems has not yet been demonstrated. However, large C^3I S2 architecture models have been built that support the change management process [7, 8]. The Air Warning Mission end-to-end model discussed in Section 5 is such an example.

Scoping the size of the models required to manage change within the tactical aerospace C^3I S2 is strongly dependent on the set of questions to be answered. Clearly, no single model (or tool) or set of models (or suite of tools) can be expected to address all of the topics mentioned above. However, by understanding the types of questions to be addressed, an Information Model (IM) can be created to understand the scope and level of detail of the information captured by the model(s). The next section discusses some representative questions related to change management at the S2 level, as well as at the systems level.

3. CHANGE MANAGEMENT QUESTIONS

The goal of the MBSE approach is to provide information in useful forms that support NATO decision makers in addressing "what if?" questions that will dictate the evolution of the tactical aerospace C^3I S2. Decision makers, program managers, and warriors must address questions that include:

- What are the effects of policy changes on my missions, requirements, systems, and their operational effectiveness?
- What are the capabilities of existing assets, including duplication, constraints, and shortfalls?
- For given scenarios, what are the expected outcomes under various deployments, using different asset suites?
- What are the measures of success and how do assets (systems, models and simulations [M&S], bioware) support these measures?
- What happens if/when certain systems are retired?
- Should existing systems be modernized or must new systems be acquired?
- What is the current status (baseline) of tactical aerospace C^3I, what is being acquired or modernized, what requirements are being met, and what are their shortfalls?
- What assets (C^3I systems, M&S, organizations, agencies, contractors) are best suited to perform certain missions, studies, or analyses (i.e., how to apply the right assets to the right job)?

Within the tactical aerospace C^3I S2, existing systems are periodically upgraded, with new systems continually integrated into the operational S2. An effective C^3I capability can only be sustained if impacts across the S2 are understood well in advance of implementation. Since these NATO assets are under the control of multiple organizations, the challenges faced in maintaining an effective C^3I capability are even greater than with a S2 maintained by a single organization.

Integration across multiple systems needs to be accomplished from several SE aspects. For example, software developers and maintainers focus on designing and testing software for individual systems. A cross-system integration focus is needed to ensure that the individual development and maintenance releases gracefully integrate into the operational S2. Key aspects to address in controlling the tactical aerospace C^3I S2 evolution involve system-wide change management, configuration control, and identification of modernization needs and opportunities.

To accomplish integrated change management, several questions need to be addressed to ensure that requirements and changes are designed and consistently implemented across systems. At an engineering level, such questions include:

- What are the existing and target architecture baselines?
- What systems and software are affected by changes?
- What are the cost, schedule, and performance impacts of changes?
- What integration and testing coordination is required for cross-system changes?

Key questions to address in system-wide configuration control include:

- How to track software, hardware, and document changes across systems.
- How to keep design and testing schedules synchronized.

Perhaps the most difficult aspect to address in controlling S2 evolution is where to spend limited funds for re-engineering or upgrading of legacy systems. Since software plays a determining role in the overall

cost of a C^3I system, understanding the evolution of software modifications is a key factor. Questions to address in determining best return on investment related to improving tactical aerospace C^3I flexibility and lifecycle costs include:

- Which software is being changed repeatedly?
- Which software changes are the most expensive?

The issues described above must be addressed from a S2 viewpoint to avoid local changes to individual systems that unknowingly have negative impacts on other systems.

The importance of precisely understanding what kinds of questions a model (or set of models) is supposed to help answer cannot be overemphasized. Once the questions to be answered are understood, the scope of the model(s) can be determined via an IM. The next section discusses some of the key aspects of an IM.

4. INFORMATION MODELS

An IM is used to define the contents of a model, or models, as well as to add structure to the model's design. Several schemes can define an IM, including an entity-relationship-attribute model or an object-oriented model, which may be based on any number of notations [9]. The IM shown in Figure 2 can be considered a "basic IM" in that the classes of all objects to be modeled are shown. To apply this IM within each phase of the lifecycle and to each task in the process shown in Figure 1 requires a decomposition of both the process tasks and the IM. Examples of such decompositions can be found in [9]. Such decompositions describe the scope and content of each model for each task within a lifecycle phase. The commonalities and differences in the decomposed object classes help identify interfaces across models that support different lifecycle phases. Without the complexities that differing tool semantics add and the configuration management challenges associated with such models, the IM is an excellent vehicle for the construction of complex models.

Figure 2 shows a basic IM used to support traceability among architecture elements. This IM has been used to develop large S2 architecture models [7] that address many of the issues discussed in lifecycle phases 2 through 4 in Section 2.2. Note that this IM is sufficiently robust to allow functional, physical, and operational views of the architecture, thus supporting the construction of both behavioral and object models. Each object in the IM can further be decomposed into subclasses, which adds further structure and constraints on the scope and content of the models. Some examples can be found in [9].

The following section discusses how the principles described above, along with the IM in Figure 2, were applied to develop the Air Warning Mission S2 architecture model. Extensions to the traceability IM to permit control of this S2 are discussed as an example of how such a model can be constructed for the tactical aerospace C^3I S2.

5. AIR WARNING MISSION MODEL

5.1 Use of RDD-100

The Air Warning Mission architecture is modeled using the COTS SE tool, Requirements Driven Development, RDD-100. (RDD-100 is a registered trademark of Ascent Logic Corporation.) The RDD-100 model captures the functional, physical, and operational views of the S2 architecture in a single data store. Information is extracted via customized reports that assist systems engineers in identifying cross-system impacts and understanding the scope of the changes to its supporting infrastructure. To facilitate the software maintenance process, data regarding software changes can be

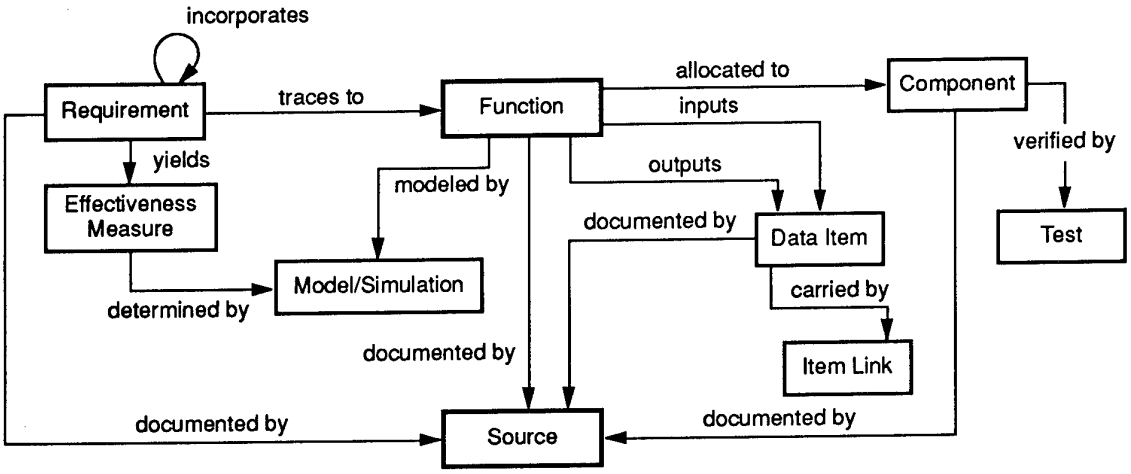


Figure 2. Basic Information Model

maintained and periodically reported. This information integration across the Air Warning Mission, as well as identifying candidates for software re-engineering.

The views extracted from the RDD-100 data store represent a set of shareable products that can be used to extract data from other architecture models supporting other projects and S2. The sharing of these customized reports represents a distinct advantage in using COTS SE tools like RDD-100.

5.2 Use of the Model

The Air Warning Mission model is one of three architecture models built to capture the warning missions of the Integrated TW/AA mission. Systems modeled include the sensor sources, communications systems, command and control systems, and the forward user locations. The level of detail captured in the model is sufficient to trace information flows associated with any message within the Air Warning Mission S2. Inter-mission traffic across models is handled via the use of external pointers within the model generating the inter-mission traffic and entry points within the architecture models receiving the traffic. To date, these models only capture normal operational behavior. Test and simulation modes, error and recovery procedures, etc., are not modeled. Furthermore, not all of the IM shown in Figure 2 is currently captured. Full extensions that include all requirements of these as-built systems, along with M&S traceability, are part of work yet to be performed.

The IM in Figure 2 does not indicate the level of detail of the information captured in the model. Capturing message-level behavior translates into modeling functions that are allocated to software components at or above the computer software component (CSC) level and associated hardware components containing the CSCs. As described below, modeling to this level of detail allows analysts to determine to the CSC level what software will be impacted by proposed changes. In total, five C^3I systems are modeled to this level of detail (representing 2.5 million lines of developed code), while some 30 or more systems are modeled to a far lesser degree to show end-to-end information flows.

Figure 3 shows the overall IM used to support change management. Note that this IM is a direct extension of the basic IM shown in Figure 2. A brief description of the IM object classes shown in Figure 3 follows:

- **Approved Change.** The actual change(s) implemented as a result of the Implementation Decision. The "correlated" Approved Changes collectively represent the total set of changes resulting from any single Proposed Change within a system.

- **Component.** Any hardware, software, or bioware that is "allocated to" perform any function. Levels of detail range from single systems down to CSCs.

- **Data Item.** Represents either message, display, alarm, or database information. Groups of any of these elements may be data items as well.

- **Effectiveness Measure.** This represents how a satisfaction of a requirement is measured in terms of success criteria. Quantitative performance measures are generally used.

- **Function.** A mission-driven operational function (e.g., journal a message) performed at or above the message level. Note that no system-driven functions (e.g., memory management) are captured.

- **Implementation Decision.** The decision and supporting rationale for choosing a particular alternative from the Implementation Strategy.

- **Implementation Strategy.** The possible alternatives for implementing the Proposed Change.

- **Item Link.** Any communication link (physical or logical) that "carries" a data item.

- **Model/Simulation.** This represents a performance simulation or model that is specifically created to assess the effectiveness measures associated with quantitative requirements.

- **Proposed Change.** Any proposed change to the operational Air Warning Mission.

- **Requirement.** Any program requirement found in the system operational requirements document(s).

- **Source.** Any source of information used in the model. These include formal deliverables, documents, briefings, expert comments, meeting minutes, etc.

Information is extracted from the model in views that support SE and software maintenance change functions. The creation of the report templates (i.e., views) is a software development task supported by RDD-100-supplied tools and windows. Available reports are listed below:

- S2 engineering
  - End-to-End Trace Reports
  - Architecture Description Documents
  - Cross-System Impact Assessments

- Software maintenance
  - Baseline Modification Summary
  - Software Component Change History

The information contained within these reports is used to support change management within the Air Warning Mission. Details concerning the content of these reports can be found in [7, 8].

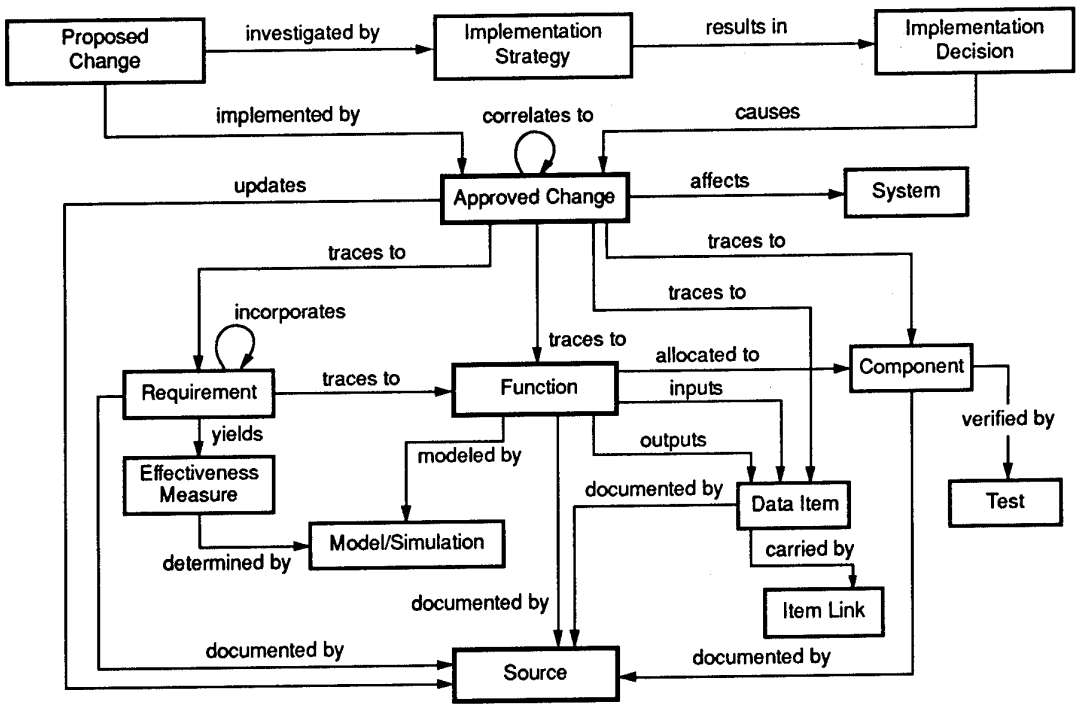


Figure 3. Change Management Information Model

An important aspect of this change management process deals with the identification of what source documentation must be updated. Multiple Interface Control Documents (ICDs) must be maintained as part of the configuration management of the Air Warning Mission S2. The models can relate the descriptions of the system objects (components) with sections of the ICDs, allowing documentation managers to more easily identify what ICDs need to be changed. This also helps ensure that the models and documentation are up-to-date and consistent. This also reflects a key part of the rationale for this model development, namely to provide pointers for systems engineers, domain-specific engineers, and configuration managers that allow them to more efficiently identify cross-system impacts and related ICD changes at a low level of detail.

The Air Warning Mission model described above lends itself to understanding "what if?" questions associated with the evolution of the tactical aerospace C^3I S2. Considerations for identifying and tracking objects of small cross sections (such as cruise missiles) or the addition of new missions, such as Theater Missile Defense, can be explored through the use of these models. Questions regarding functionality of command and control centers and their supporting communications and processing and display systems can be assessed. Determining whether existing facilities can be upgraded or if new ones must be built to meet new performance requirements can be investigated through "alternative behavior views" within the RDD-100 functional behavior model.

The Air Warning Mission model is a proof-of-concept showing how MBSE principles can be implemented through a single COTS SE tool, RDD-100. Although this work could scale up to model the tactical aerospace C^3I S2, no single tool can be expected to meet all the needs of the decision makers controlling the evolution of such a complex S2. Furthermore, investments in tools that currently model aspects of the tactical aerospace C^3I S2 should be leveraged, not duplicated or re-invented for the sake of using other tools. Use of an ISEE shows promise in meeting the challenges associated with such efforts. The next section addresses the ISEE concept.

6. INTEGRATED SYSTEMS ENGINEERING ENVIRONMENTS

The implementation of the MBSE method is accomplished via an ISEE. An ideal ISEE should allow legacy models and tools, as well as new tools and their models, to be used within a single integrated environment.

6.1 ISEE Overview

The goal of an ISEE is to allow modelers to use any tool to develop models and extract information in any desired way from a common data store. The fundamental ideas are: the information captured is important, the investment to gather information and build accurate models is significant, while the tools used to accomplish these tasks will come and go. ISEEs have the following characteristics:

- Designed to support existing processes
- Composed of an integrated set of COTS (preferred) tools and methods
- Underlying information management structure allows non-obtrusive sharing of data across tools
- Transparency of data sharing via a common, single-user interface
- Extensible to allow multiple underlying COTS database management systems (DBMSs) and SE tools
- Network accessible on a client-server architecture

Presently, no ISEE possesses all these characteristics. There are, however, two promising technical approaches being explored to build such an ISEE. These two approaches differ in the underlying supporting technologies being used. The basic approaches use:

- Repository COTS products that adhere to open standards such as the Federal Information Processing Standard (FIPS) 156 for Data Repositories
- Object-oriented COTS products that adhere to the Object Management Group (OMG) Common Object Request Broker Architecture (CORBA) standard

These approaches depend on the use of both open standards and their related products to provide the underlying technology. The use of such standards are viewed as enablers in that the COTS products used to build the ISEE are more easily integrated when common standards are used. Even so, the amount of "glue code" required to integrate these COTS products is significant and requires knowledge of product application programming interfaces (APIs). Additional challenges faced in the development of an ISEE are mentioned in Section 6.3.

In-depth discussions regarding these issues or the two approaches mentioned above are beyond the scope of this paper. However, an example of the use of a repository approach can be found in [10], while an approach using object-oriented technologies is described in [11]. Although still in the proof-of-concept phases, these ISEE developments are showing promise in possessing the desired characteristics of an ideal ISEE.

The structure of an ISEE is partly determined by the tools used to build the models that support the decision making process. Understanding the scope of possible tools to be used provides insight regarding the investment required to answer certain change management questions. For example, management may choose not to invest in a certain tool or integrate a legacy tool and associated models into an ISEE, if the investment to do so is not compensated for by the value gained by the integration. The next section provides a sample listing of some of the more popular available COTS application tools, which are candidates for an ISEE.

6.2 COTS Application Tools

An ISEE should be applicable across the lifecycle of the tactical aerospace C^3I S2. A suite of COTS tools exists today that can effectively cover a broad range of the expectations discussed in Section 2.2. Some examples of tools and their applications follow to demonstrate the richness of available COTS application tools. (Note: It is impractical to list all available tools. Inclusion or exclusion from the list does not imply a thing.) Following the listing, some challenges and problems associated with using such a variety of tools in a common ISEE are discussed.

General Systems Engineering tools that permit modeling within each phase of the lifecycle, thus capturing a wide variety of the MBSE characteristics previously discussed:

- CORE
- RDD-100
- SEE Cradle
- SLATE
- System Architect

Requirements Management tools, which focus attention on requirements and their change management throughout the system's lifecycle:

- DOORS
- QFD/Capture
- RTM

Process Modeling tools that allow process capture, whether for systems, S2, or the way in which business is performed, and, in some cases, support process enactment:

- BPWin
- Design/IDEF
- ProCap
- Process Weaver
- ProSim
- SynerVision

Simulation tools, which support executable models to understand performance questions. Discrete and/or continuous modeling are supported:

- BONeS
- Extend
- Foresight
- QASE
- SES/Workbench

Numerous domain-specific tools can be added to this list. For example, tools that support configuration management, test, security, software re-engineering, and hardware design could also be included as viable candidates for inclusion in ISEEs at the application level.

Progress is being made toward the integration of COTS tools across application domains, but at a far simpler level of sophistication than the efforts referenced in Section 6.1. For example, interfaces exist between such tools as RDD-100 and SES/Workbench, RTM and Foresight, System Architect and RDD-100, DOORS and Teamwork (a software engineering tool), Design/IDEF and RDD-100, etc. These pairwise solutions are accomplished via such mechanisms as APIs or interface definition languages (IDLs). Such implementations are labor-intensive and are frequently imperfect in their translations. Tool semantics and syntax differences make 100% translations impossible. In spite of these issues, pairwise interfaces are a step in the right direction and demonstrate the necessity for COTS tools to be integrated in a closely coupled fashion.

The rich set of tools listed above has negative, as well as positive, points. The value of having such a suite of tools is the user's ability to choose the right tool(s) for the right job without investing in the development of one's own unique tool. Negative aspects include the fact that no tool is ever exactly what is needed, and the reality that COTS tools are not designed to interact with one another. These and other challenges facing an ISEE are discussed in the next section.

6.3 Challenges in Developing ISEEs

Challenges in developing a fully functional ISEE are related to the rich set of available COTS tools, the historical use of in-house developed tools, the large number of models built to address various aspects of change management, and the general bottom-up approach to the use of tools. Some of the more important challenges, both technical and cultural, facing the success of an ISEE include:

- COTS tool integration does not exist within any application domain (e.g., requirements management) or across domains (e.g., between systems engineering and software engineering).
- Tool interoperability and integration is difficult since COTS tools semantics and external interface definitions (e.g., APIs) are different and, in some cases, not published.
- Simultaneous access to ISEE data via multiple tools by several engineers raises complex configuration management, version control, and data access issues.
- The migration of legacy tools and models to richer environments, while leveraging existing investments, is not common practice.
- The construction of flexible IMs that accommodate data and semantic structure differences across tools and different tool domains is an art rather than a science.
- Early lifecycle cost justification (return on investment) of a MBSE approach using an ISEE is not easily demonstrable, since returns are experienced in later lifecycle phases (i.e., cost avoidance).
- Changing the culture from a document-driven design and maintenance philosophy to a model-driven approach can be a challenging experience.
- Taking a S2 perspective across the tactical aerospace C^3I S2 demands some visibility into systems and domains that was previously not required.

7. CONCLUSIONS

MBSE, as implemented by an ISEE, is a promising approach to creating a technical management structure to control the evolution of the tactical aerospace C^3I S2. Proof-of-concept modeling of MBSE principles using the COTS SE tool RDD-100 has been shown feasible for C^3I systems via the modeling of the Air Warning Mission S2.

Implementation of MBSE methods via an ISEE is the overall goal now being pursued through the use of integrated standards-based products using underlying technologies such as repositories and object-oriented modeling. The current state-of-practice regarding tools integration (i.e., migration towards an ISEE) is through pairwise integration of tools using APIs or IDLs.

Major challenges facing this work include:

- Incorporation of legacy tools and models
- The integration of COTS tools
- Scaling up of models to accommodate the tactical aerospace C^3I S2 levels of complexity
- Acceptance of a model-driven approach to system design and evolution

Next steps in demonstrating the feasibility of using MBSE and ISEEs to help manage the tactical aerospace C^3I S2 include expanding current modeling efforts to include:

- Adding database features capable of generating text and graphics-based reports and performance statistics.
- Building behavioral and object models of the tactical aerospace C^3I S2.

- Using these models to explore "what if?" questions pertaining to new threats and theater scenarios.

- Performing fixed, deployed, and employed asset architecture analyses to truly assess the value added in implementing a MBSE approach.

Approaching the 21st century, investments should be made in two major technical areas:

- The development of an ISEE that is capable of integrating legacy tools and models, along with new COTS SE tools, and

- The creation of a faster than real-time simulation capability that can proactively determine the course of action of a deployed tactical aerospace C^3I S2 (i.e., manage change in a real-time environment).

8. ACKNOWLEDGMENTS

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Horizon

An Architecture Management and C4I Capabilities Planning Process for the United States Air Force

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1. SUMMARY

A methodology for managing Command, Control, Communications, Computers and Intelligence (C4I) interoperability problems in a multi-mission environment is presented. The effort, designated Horizon, was sponsored by the United States Air Force (USAF). It is a disciplined top down process for managing and directing architectures starting at a high level.

The essential elements of interoperability are defined. Mission operations boundaries are formulated to serve as a framework for construction of top level and mission level views of the C4I elements. Information flow between C4I elements is described, and the combination of the views and the interoperability attributes are organized into a database.

Commercial-off-the-Shelf (COTS) software was used to develop a tool, designated Horizon Link, to support the process. The database may be expanded to accommodate specific user needs and to support specialized analyses. The use of the database to support a communications systems analysis within the framework of the defined C4I interoperability model is described.

The Horizon process has been applied to the USAF in formulating top level views of C4I interoperability supported by a database and in managing C4I issues. It may be extended to other Services or mission scenarios. Recently, the Horizon process has been extended into Europe, the Pacific, and the Joint Operations environment. It is the joint environment application that may be of interest to NATO. Considering this, a deployed Joint Task Force (JTF) scenario is developed, and the flexibility of the Horizon process is illustrated, resulting in a top level portrayal of C4I elements in support of joint operations.

2. BACKGROUND

In the United States (U.S.), the Air Force Deputy Chief of Staff for Command, Control, Communications and Computers (DCS/C4) was directed by the Chief of Staff of the Air Force, in 1992, to be responsible for directing and managing all of the architectures in the Air Force dealing with interoperability. Intelligence support was included in the scope of responsibility, as well.

The MITRE Corporation's Department of Defense (DOD) Federally Funded Research and Development Center teamed with Headquarters Air Force under the leadership of Lieutenant General Carl O'Berry, DSC/C4, to develop a process, methodology, and tool which could be applied to managing the C4I architectures and interoperability issues across major Air Force mission areas, between and among Air Force and other DOD services and agencies, and between the Air Force and our Allies.

The objective was to develop a top down process, starting at the highest Air Force level, and produce a portrayal or presentation of C4I interoperability which could provide a common basis, supported by a database, for identifying and resolving critical issues. The process and tool were to be applied in providing direction regarding standards between all Air Force C4I systems and between the Air Force and other U.S. and Allied systems.

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At the outset, the major Air Force mission and support areas were established and a set of boundaries defined which would be the concern of the Air Force at this high level. The architecture management process that ensued focused on one Air Force office for the integration of architectures, and identified to the Air Force major Commands and agencies responsible for architectures; boundaries and responsibilities, while at the same time allowing design-free input in the systems and architectures at a lower level.
Once the process and methodology were formulated and accepted within the Air Force, "strawman" views of C4I interoperability were developed, first for the Air Force as a whole; i.e., worldwide; then at the next or second level for each defined mission and support area. A supporting database describing information flow, interoperability attributes, and issues was also developed. This entire data set was coordinated within the Air Force and a forum, called an Architecture Steering Group, was established to review and manage the issues using the common context of the C4I views developed for this purpose. The first meeting of the Architecture Steering Group was held in September 1994.

The tool, designated Horizon Link, which contains the Air Force C4I views or diagrams and the supporting interoperability tables, was designed, developed, and delivered to the Air Force DCS/C4 in February of this year.

The process and tool have been applied in extending C4I interoperability architecture management to two theatres, Europe and the Pacific (the latter included Korea); one of our Allies, the United Kingdom; and they're currently being looked at for JTF as well.

3. COMMAND, CONTROL, COMMUNICATIONS, COMPUTERS AND INTELLIGENCE (C4I) INTEROPERABILITY DEFINITIONS

The Horizon program emphasizes C4I interoperability and facilitates identification, tracking, and resolution of interoperability problems across major mission areas and Commands. It is a top down process for managing and directing C4I architectures starting at a high level. It is not an architecture or system design tool, but it is structured so that it can be extended into specific systems analysis areas, as shall be shown later in this paper.

Interoperability has been defined in many ways; however, appropriate to the C4I interoperability addressed here is the U.S. Joint Chiefs of Staff (JCS) 1989 definition under the C4I for the Warrior initiative which offers this definition: "The ability of systems, units, or forces to provide services to, and accept services from, other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together. . ."

The essential elements of C4I interoperability are shown in Figure 3-1. Since the ultimate objective is to ensure interoperability among fighting forces in operations during and through the several classically defined stages of hostilities; i.e., tension, crisis and conflict; the Horizon process must embrace these four essential elements:

1. Compatible communications and Automated Information System (AIS) interfaces.
2. Compatible messages and formats.
3. Compatible databases and software applications programs.
4. Compatible operating procedures.

Element 1 considers the electronics and systems that enable the flow of information between forces. Elements 2 and 3 provide a basis for achieving understanding in the information exchange. Element 4 emphasizes coordination of operations among, and within, multi-national forces.

It is the integrated set of these essential elements that, when achieved, affords the C4I interoperability needed to confidently meet any threat.

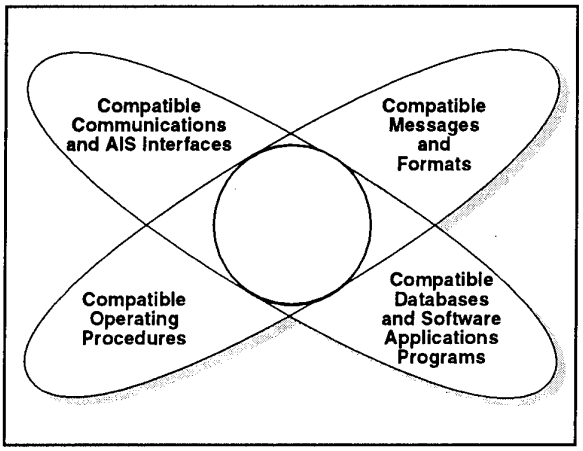


Figure 3-1. Essential Elements of C4I Interoperability

4. HORIZON: THE METHOD AND THE TOOL

4.1 Objectives of the Capability

It is the overall objective of the Horizon process to support the direction and management of C4I architectures and to ensure the interoperability of C4I systems. Its emphasis is on the management of C4I issues, particularly those that involve cross mission or force operating interfaces; i.e., the identification, analysis, cataloging, tracking, and resolution of those issues.

The management of issues is accomplished within the framework of a "system of systems" top level view of C4I elements of the forces of interest supported by lower level mission area views and a database. This information set, organized to meet the C4I manager's and planner's needs, provides a common method and point of reference for commanders and staff to understand and discuss interoperability parameters and issues. At the highest level, C4I nodes and the information flow between them are portrayed to facilitate the objectives.

The Horizon database, with its C4I "system of systems" diagrams and its lower level mission area diagrams supported by interoperability attributes, as shown in Figure 4-1, provides a framework for the management of issues. Ultimately, the top level issues so identified are brought to a forum of principals for resolution. In the USAF, the forum of principals is an Architecture Steering Group chaired by the Deputy Chief of Staff of the Air Force for C4 with participating and voting members from the major Commands and field operating agencies and, more recently, the United Kingdom in "participant" status.

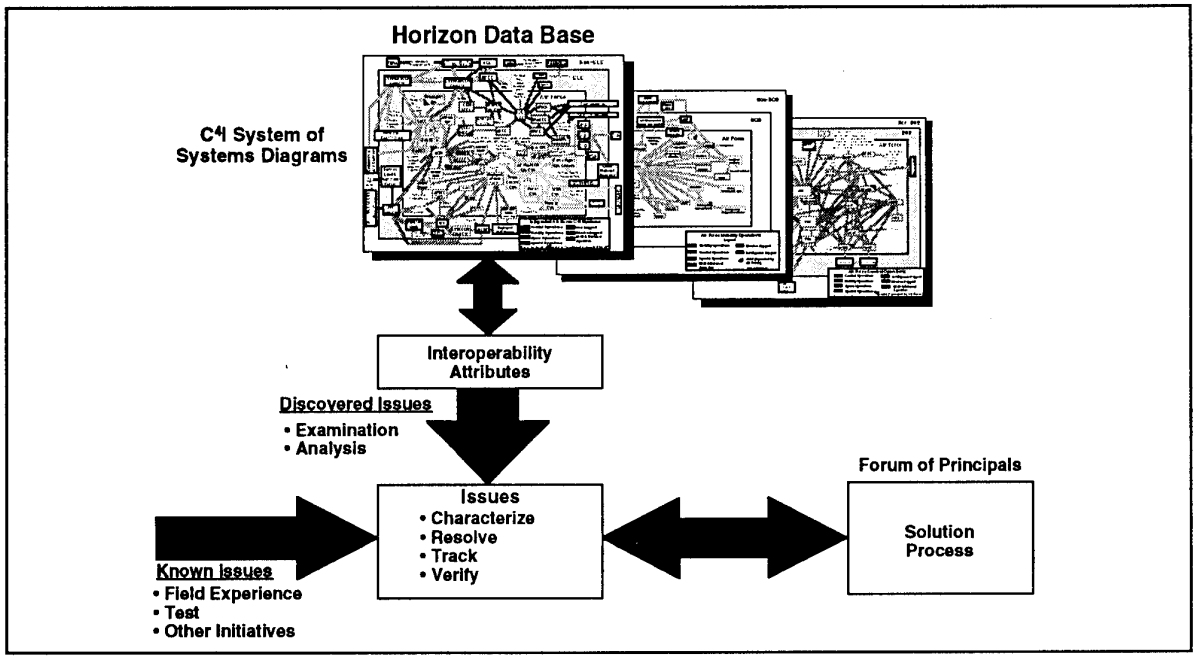


Figure 4-1. Sample Use of Horizon Data Base to Identity and Manage Issues

It is a further objective of the Horizon process to provide the basis for derivative special analyses in order to examine, for example, communications systems which provide for the connectivity between C4I elements; or, the automated information systems that are the end terminals supporting the warfighter; or, specific aspects of the operations of the forces under central or distributed control; or, the impact on C4I interoperability of the time-phased introduction of new capabilities and systems.

4.2 The Model

The Horizon program and database provide a top down C4I interoperability architecture management process for managing, controlling, and directing architectures and systems integration at a high level. The general Horizon process depicted in Figure 4-2 establishes mission operations boundaries and provides for the application of standards which can be utilized to ensure that C4I interoperability is achieved between systems for combined arms operations, both national and multi-national. After the defined mission area set is established to facilitate the boundary definition for management purposes, a baseline or "as is" portrayal of C4I elements and interoperability attributes is developed, employing the methodology developed in Section 4.3. This can be used to provide guidance to mission system and lower level architectures. It is important to note that the model and process focus on managing C4I issues and interoperability at the boundaries between defined mission areas and between national service elements and non-defense and allied forces while allowing design freedom within mission systems.

Interoperability issues derived are analyzed and resolved employing international and DISA standards and a set of Technical Reference Codes, while considering the critical factors shown at the bottom of Figure 4-2. The outcome of these steps may influence either or both the future integrated C4I system of systems and the planning and acquisition process.

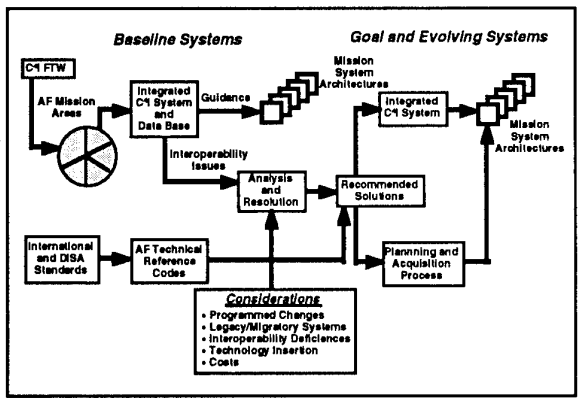


Figure 4-2. General Horizon Process

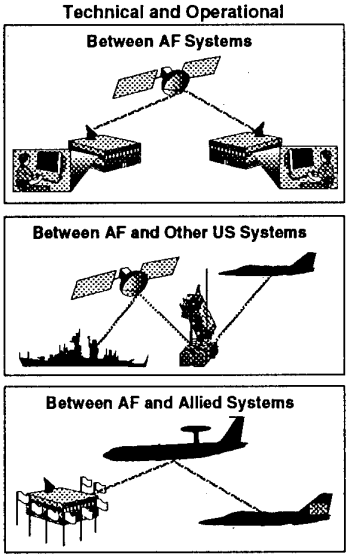


Figure 4-3. Horizon Interoperability

In the U.S., the process has been developed and applied in managing the identification and resolution of C4I interoperability issues between USAF major mission weapon systems and they are being looked at as a means of addressing issues between USAF and other DOD and non-DOD and Allied systems (Figure 4-3).

The model incorporates and depicts only C4I elements, as illustrated in Figure 4-4 and described in Figure 4-5. As cited earlier, the diagrams do not include: people (commanders, etc.), organizations, buildings, facilities, or systems. The last item noted, C4I systems, while not shown on the Top or Second Level Diagrams developed in the methodology section (unless they fall into one of the element categories on Figure 4-4), will be manifest in the interoperability database that characterizes the information flow between the C4I elements diagramatically depicted. Thus, the model strictly adheres to the portrayal of C4I elements and the management of C4I interoperability issues.

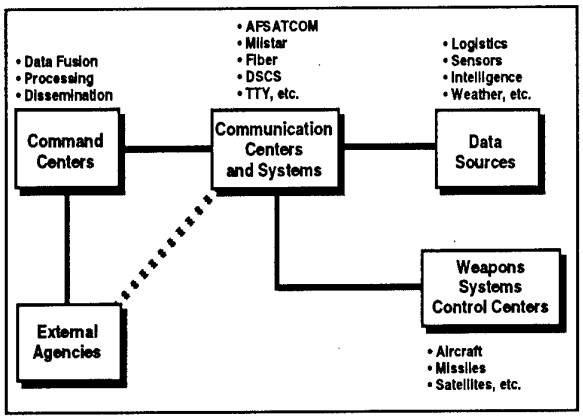


Figure 4-4. The Horizon C4I System Model

- **Command and Control (C^2) Node**
  - **A Command Post or Central Command and Control location, where sensor and other information is processed and integrated from which information is sent to a higher or lateral authorities and/or direction is provided to executing elements and forces**
- **Communications**
  - **Means of conveying information of any kind – from one person or place**
- **Computers**
  - **Automatic Information Processing Systems that receive, manipulate and present information from multiple sources**
- **Intelligence**
  - **The product resulting from the collection, processing, integration, analysis, evaluation, and interpretation of available information concerning foreign countries or areas (or forces)**

Figure 4-5. C4I Elements

4.3 Methodology

The first step in the Horizon process is to determine the mission area set to be managed from an architectural and C4I interoperability perspective. In the case of USAF, the defined major mission and support areas are six-fold and include: Space Operations, Combat Operations, Mobility Operations, Special Operations, Intelligence Support, and Mission Support (e.g., logistics, medical, personnel, etc.) These are shown in Figure 4-6. The arrows in the diagram are intended to point out that the process focuses on the C4I issues at the boundaries

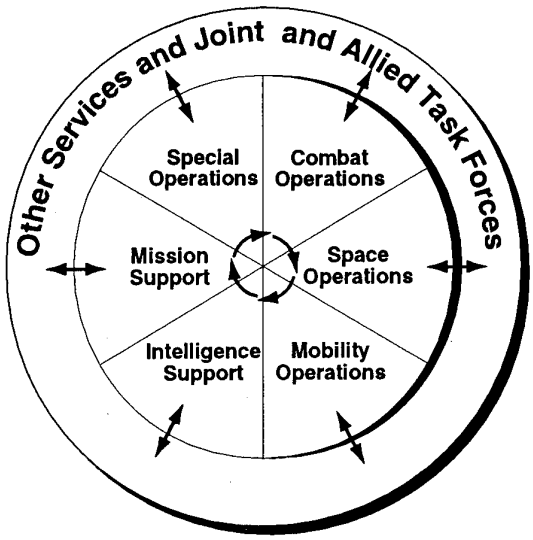


Figure 4-6. Air Force Mission and Support Areas

between mission areas and between the Air Force and other Services and our Allies.

The next step is to construct the Top Level and Mission Area (Second Level) diagrams. This is illustrated by the series of charts in Figures 4-7 through 4-9. The portrayal format used in all of the diagrams is shown in Figure 4-7. The center and largest area of the diagram is devoted to the enterprise or "integrated system of systems" of interest. For this illustration, we have selected the USAF C4I integrated system of systems diagram for the portrayal in the center. The middle, or inner border, is allocated to "Other Department of Defense and Service Unique C4I Elements and Interfaces." Only the major C4I elements in this category with information flow interfaces with elements in the center of the diagram are shown here. The outer border is allocated to C4I elements of Allies and non-defense interfaces for the elements in the center of the diagram. Figure 4-8 shows that areas of the center of the diagram are allocated to the defined mission areas which, for purposes of the illustration, are taken from those shown earlier in Figure 4-6. At this point, known interfaces external to the Air Force may be added in. DIA, for example, is a non-AF DOD interfacing C4I element and is placed in the middle or inner border. Allies and

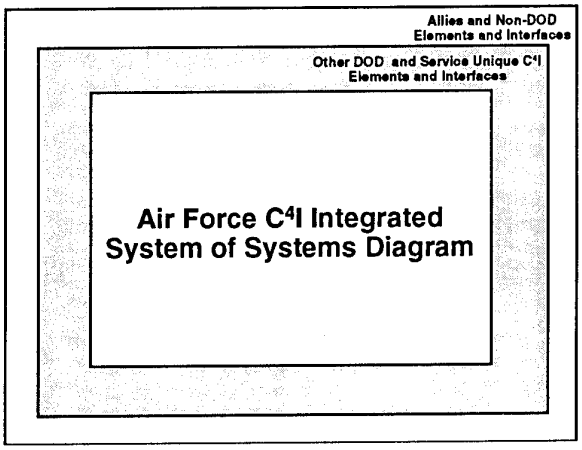


Figure 4-7. Top Level Diagram Development-*Step One*

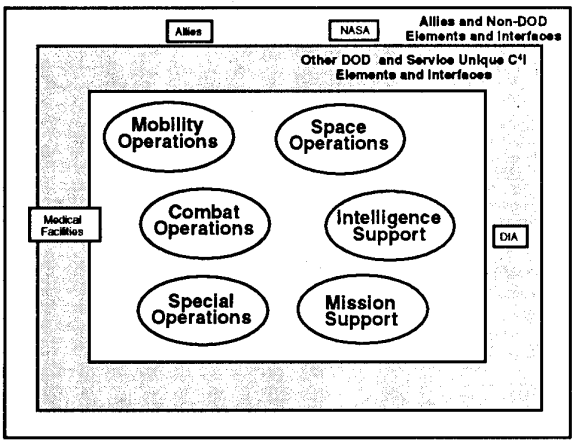


Figure 4-8. Top Level Diagram Development-*Step Two*

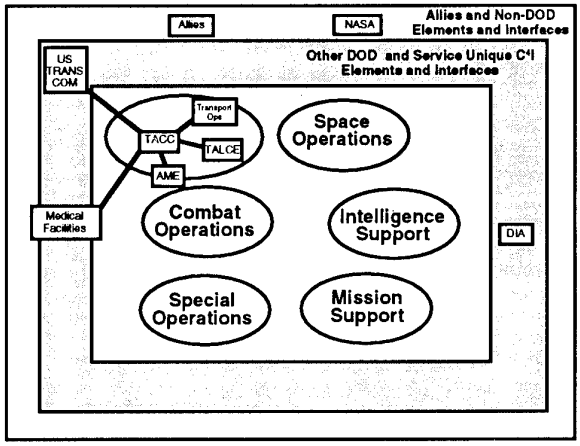


Figure 4-9. Top Level Diagram Development-*Step Three*

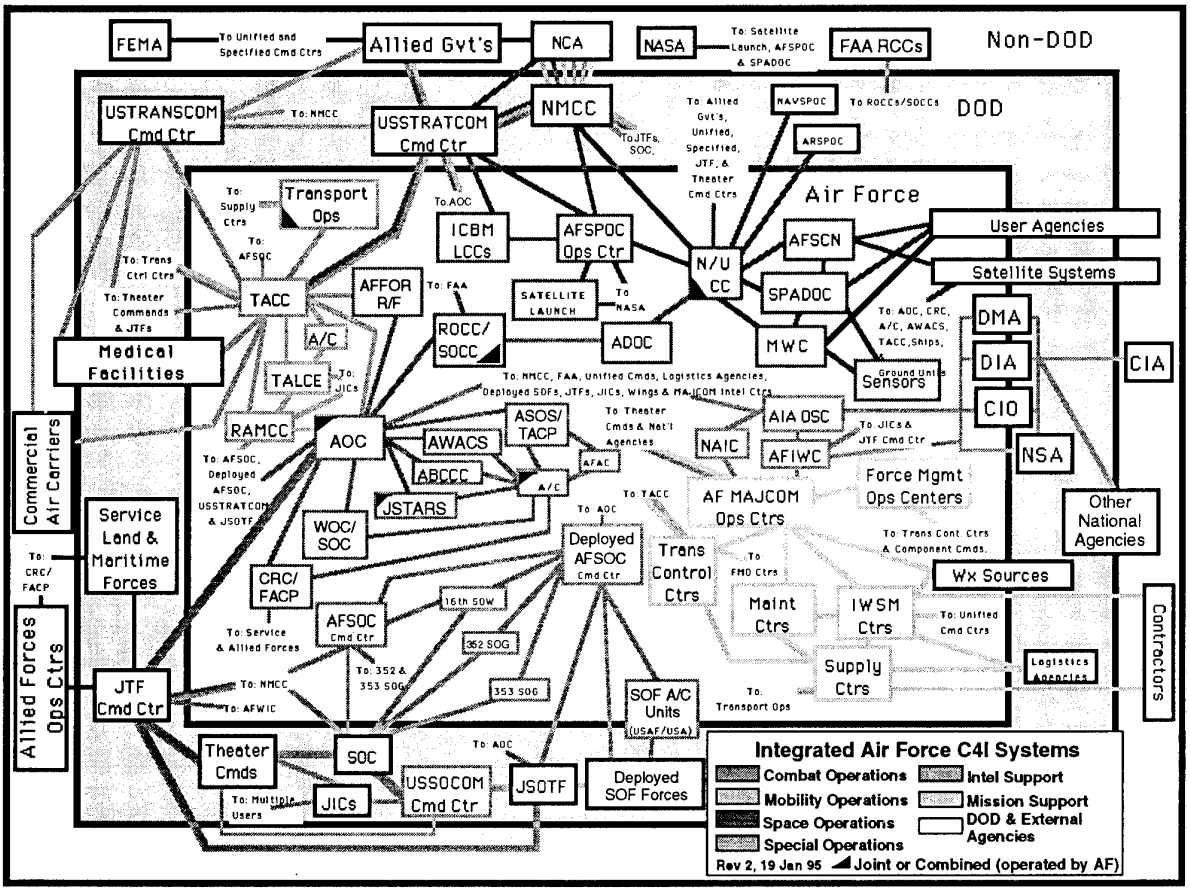


Figure 4-10. Integrated Air Force C4I Systems

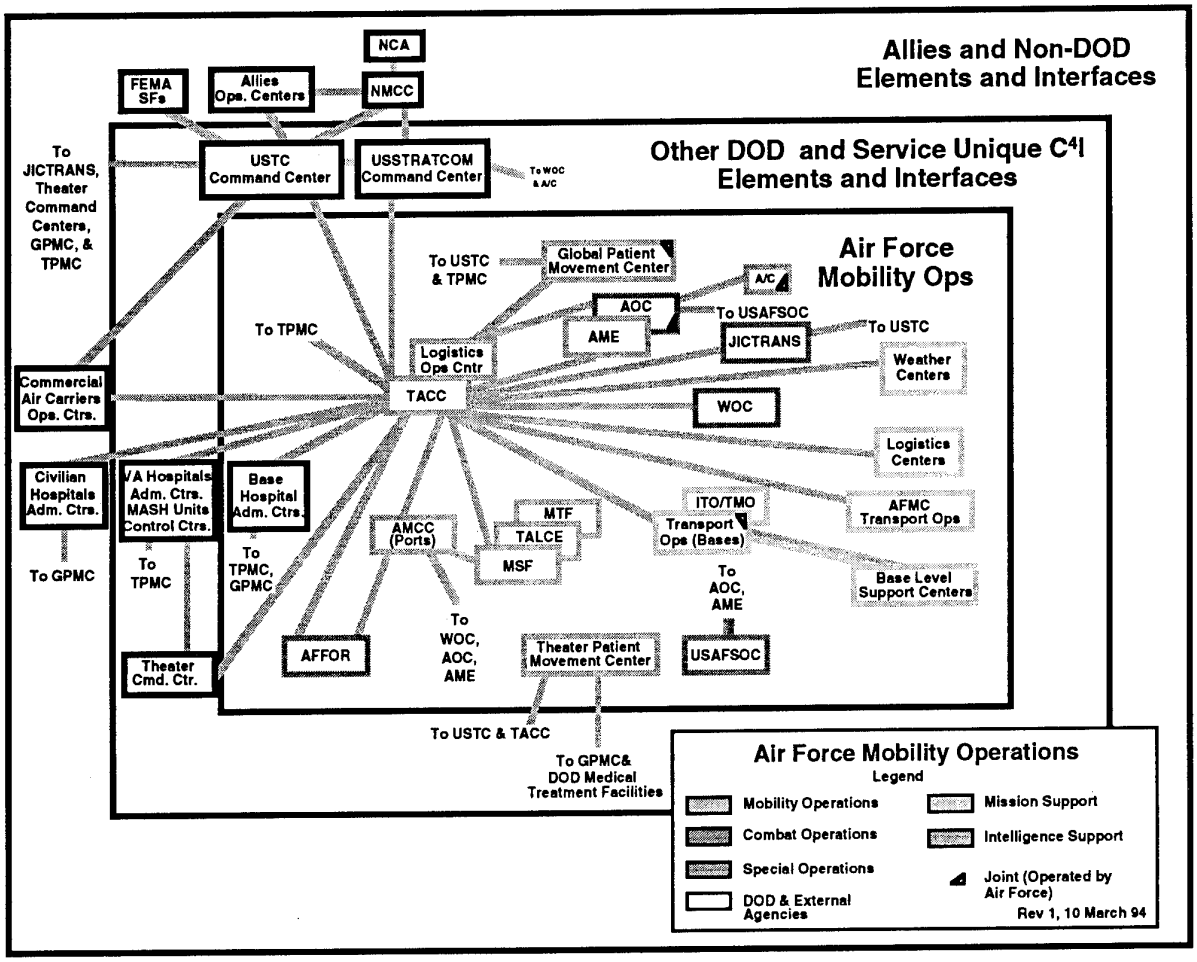


Figure 4-11. Air Force Mobility Operations Systems

NASA are examples of elements to be appropriately placed in the outside border of the diagram. Note that some C4I elements, such as those associated with medical support, necessarily cut across all three areas in the diagram.

Next, each of the mission areas are diagrammed at the very top level showing major C4I elements. In Figure 4-9, we have shown the formulation of the Mobility Operations mission diagram. Known or planned connections are then added by drawing a line between C4I elements which signifies that information flows between those elements, or nodes, as we shall begin to call them. Each of the mission areas are developed in this way until all nodes at this high or first level are shown while paying strict attention to the model. A fully populated diagram developed in this manner for USAF is illustrated in Figure 4-10.

Now the Second Level Diagrams (SLD), or mission area specific diagrams, as they may be referred to, are developed. The method of presentation remains the same, so that a common frame of reference may be relied upon for planners, developers, and operators alike. Air Force Mobility Operations has been selected to illustrate the SLD, Figure 4-11. In the case of the SLD, the entire center area is allocated to the specific mission area, thereby, providing more space for detail. Further, the middle and outer border areas may be devoted to placing only those elements with which the specific mission area has interfaces; i.e., where information flows between mission area nodes and C4I elements in the two border areas. One of these SLDs is formulated for each of the six or selected sets of mission and support areas.

The diagramming methodology developed here may continue on to lower levels to the point wherein the depictions begin to take on a physical nature, as well as operational and technical.

We now turn to the development of interoperability attributes which become part of the database supporting the diagrams. In our model, these are structured to correspond to the Top and Second Level diagrams. This section of the process is illustrated in Figure 4-12. On the upper left is shown a representation of the diagrams. The C4I nodes are labeled with numbers. If there is information flow between nodes, the intersection is represented, as shown in the "N2 Chart," shown in the lower center of the figure. The information flow data across each intersection is then defined and entered into a table structured according to the user's needs. This step is illustrated in the upper right of the figure.

Using the diagrams and information flow characterization in the way prescribed, interoperability attribute tables are developed for both the top and lower level diagrams, as shown in Figure 4-13. As one progresses from the top to more detailed levels, the interoperability attribute tables are expanded to provide greater detail concerning the information flow and interfaces.

Format and content examples for top and second level interoperability tables are offered in Figure 4-14 and 4-15. A column for entry of issues is provided in each table, so that the database can support the cataloguing, tracking, and resolution process. Please note the greater detail on the second level example. The communications link information and the end terminal Automated Information System (AIS) data are entered. These data can facilitate system dependency analyses. As will be shown later in the paper, a communications systems analysis has been conducted using as a base the information in the database constructed from the interoperability tables.

The ultimate use of the diagrams and interoperability tables is to support the identification, cataloguing, tracking, and resolution of C⁴I interoperability issues. Referring again to Figure 4-1, the issues discovery and management process is aided by the very act of diagramming C⁴I systems and interfaces at the highest and succeedingly deeper levels and using this information as a commonly understood representation of interacting forces and systems. Conflicting perceptions about specific interfaces are readily identified. More complex interoperability problems, either known or discovered, may be managed through a forum made-up of principal representatives of the mission areas or national forces. The forum would use the Horizon database as a tool to facilitate the issue resolution process.

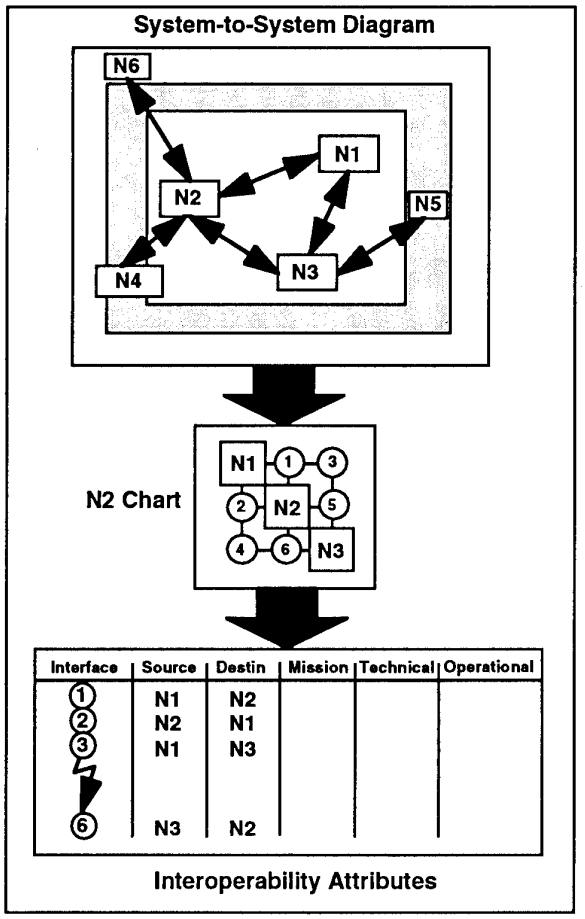


Figure 4-12. Interoperability Attributes Table Development

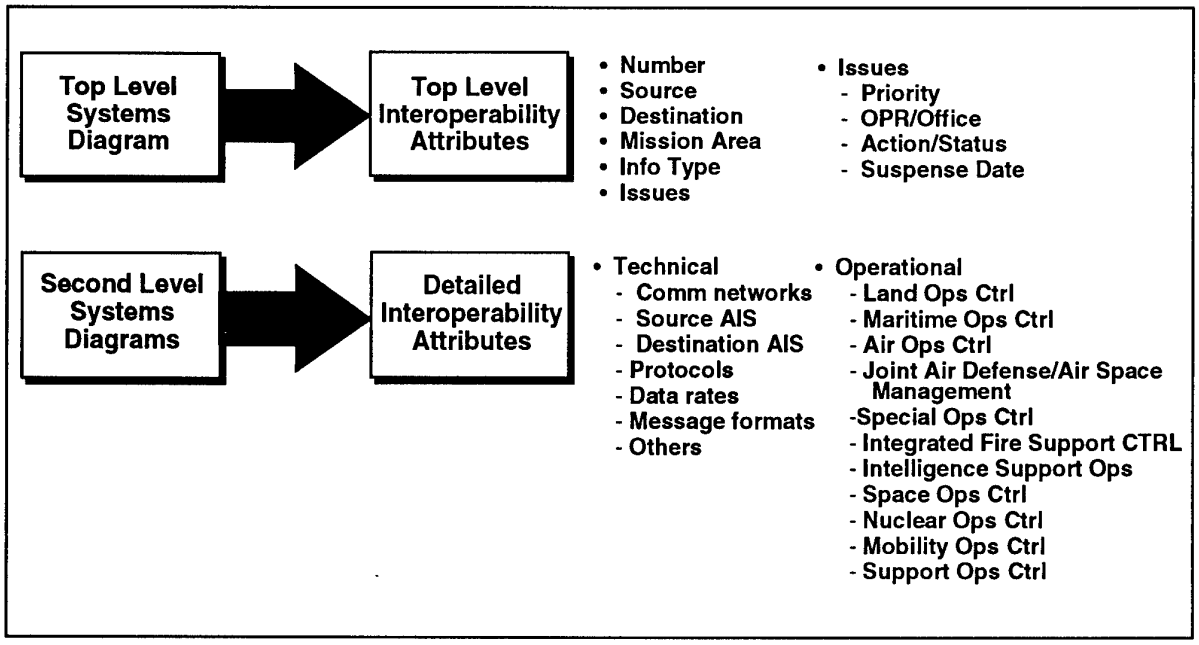


Figure 4-13. Overview of Interoperability Attributes

Number	Source	Destination	Mission	Information Type	Issues Comments
• • •					
73a	MWC	N/U CC	Space Operations	Alerts & Warning Mission Coordination System Status	
73b	N/U CC	MWC	Space Operations	CINC Assessments Direction	
74a	MWC	SPADOC	Space Operations	Launch Coordination System Status	
74b	SPADOC	MWC	Space Operations	Element Sets	
• • •					
76a	N/U CC	SPADOC	Space Operations	CINC Assessments Direction Message Release Approval	
76b	SPADOC	N/U CC	Space Operations	System Status Mission Coordination	
• • •					
89a	TACC	TALCE	Mobility Operations	Tasking & Scheduling	
89b	TALCE	TACC	Mobility Operations	Movement Status Asset Status	
90a	TACC	Trans Ops	Mobility Operations	Movement Schedules	
90b	Trans Ops	TACC	Mobility Operations	Force Movements ITV	
91a	TACC	TMO	Mobility Operations	Tasking & Scheduling	
91b	TMO	TACC	Mobility Operations	Airlift Requirements	
• • •					

Figure 4-14. Top Level Interoperability Table-*Format Example*

Number	Source	Destination	Mission	Information Type	Comm Network	Source AIS	Destination AIS	Issues
• • •								
202b	AOC	ABCCC	Space Operations	Tasking, ATD and ATD Changes				
• • •								
230a	AOC	TACC	Mobility Operations, Combat Operations	Status, Coordination				
• • •								
439a	MWC	Users	Space Operations	NUDET and Ballistic Missile Threat Information				
• • •								
512b	USOTF Ops Ctr.	AFSOC Cmd. Ctr.	Space Operations	Orders, Directives, Status, Support Requests				
• • •								
648a	TACC	Trans. Mgt. Offices	Mission Support	AMC Airlift Schedule				

Figure 4-15. Second Level Interoperability Table-*Format Example*

4.4 Horizon Link Tool

The tool developed to support the management of the C⁴I interoperability issues has been designated Horizon Link. Commercial Off-the-Shelf (COTS) software has been used to provide a user-friendly means of formulating the diagrams and entering the interoperability attributes. Our objectives were that the tool be of low-cost, available commercially, and run on both Personal Computers (PC) and Macintosh platforms. The application packages and database management software we selected are Fox Pro/SQL and Power Point, as shown in Figure 4-16. The Fox Pro software offers the desired flexibility in database manipulation. SQL offers the networking capabilities and a central database server to support local and remote users. The Power Point application supports briefing development.

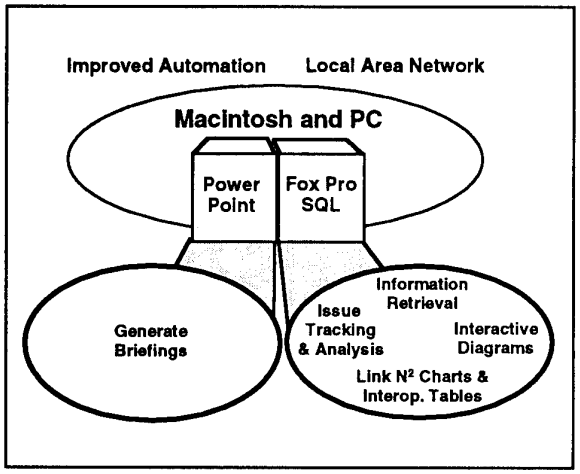


Figure 4-16. Horizon Link Tool

Recalling the database content, we have at this point the current as-built Top and Second Level diagrams and some extensions in the form of specific theatre-level diagrams, as illustrated in Figure 4-17. In addition, the database contains the interoperability attributes and data flow information, the interoperability issues for each of the top and second level views, and references to a set of operational standards and Technical Reference Codes to be employed in the evolutionary process.

The structure of the database is illustrated in Figure 4-18. At the top level is the "integrated system of systems" diagram with accompanying interoperability attributes. The next level contains the six mission and support area diagrams and supporting interoperability tables. Figure 4-19 shows the PC presentation of the node-to-node charts, wherein the C⁴I elements entered from the diagrams are listed vertically and horizontally, and the intersections between nodes are identified by an "X" entry in the matrix. The Horizon Link tool links the "X" entries to the interoperability tables, so that selection of a particular "X" will bring up on the user's screen the interoperability information concerning the selected intersection.

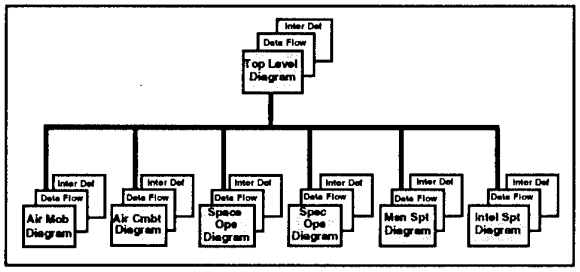


Figure 4-18. Horizon Data Base

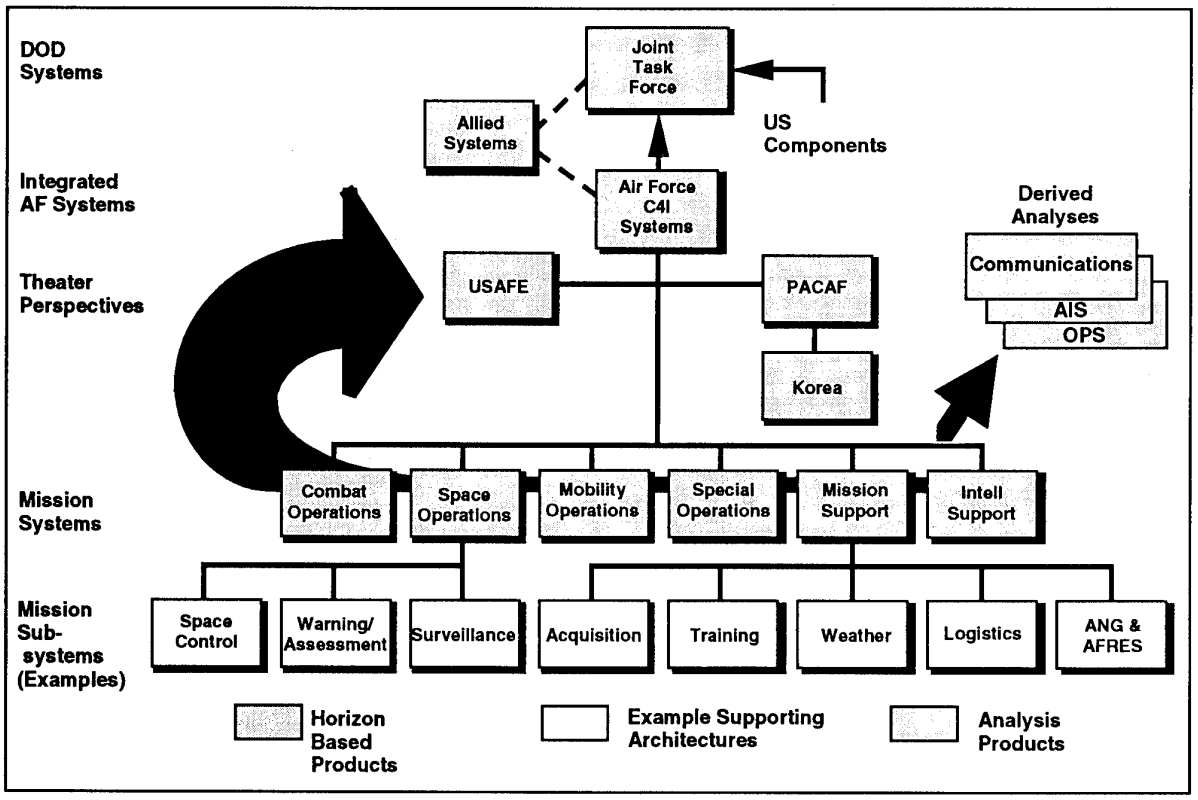


Figure 4-17. Horizon Hierarchy

The navigation features offered by Horizon Link are illustrated in Figure 4-20. Starting at the Top Level, the user, for example, may navigate down the left side by selecting a particular element for analysis. The tool can produce, in diagram form, all of the nodes with which the selected element interfaces and navigating further on the path can retrieve all of the interoperability data concerning that node.

The user may choose to navigate through the system on a mission basis. The tool supports this, as shown on the right side of Figure 4-20. First, selecting a mission area produces the Second Level Diagram of that mission area. The user may then select a particular element or elements within that mission area, and the tool will produce the mission element interoperability attributes and issues associated with intersecting nodes.

The tool supports the manipulation of the database, including adding, deleting and modifying, and offers the user a report tailoring capability, such as keyword search and reporting (e.g., locating and displaying all of the top priority issues associated with a particular mission area). The N2 charts are automatically regenerated to reflect the changes made and are linked at all levels. At this point, the diagram regeneration is manual.

In the near term, the Horizon Link configuration will be as shown in Figure 4-21 supporting a user network locally. This networkable tool can be configured, as shown in Figure 4-22. Thus, the C4I diagrams and interoperability tables can be made available over a wide-area network, linking major commands or national force representatives, to a centrally managed but distributed database. Thus, users may interact, employing a common portrayal of C4I elements and data, and identify and participate in the resolution of issues.

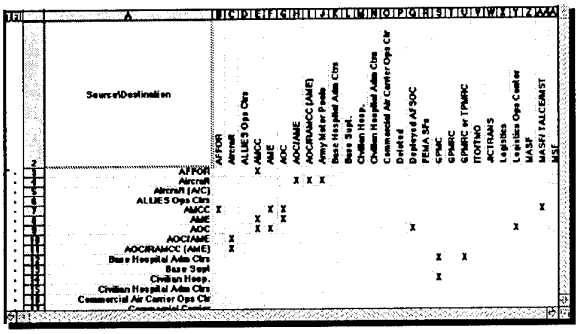


Figure 4-19. Node-to-Node PC Format

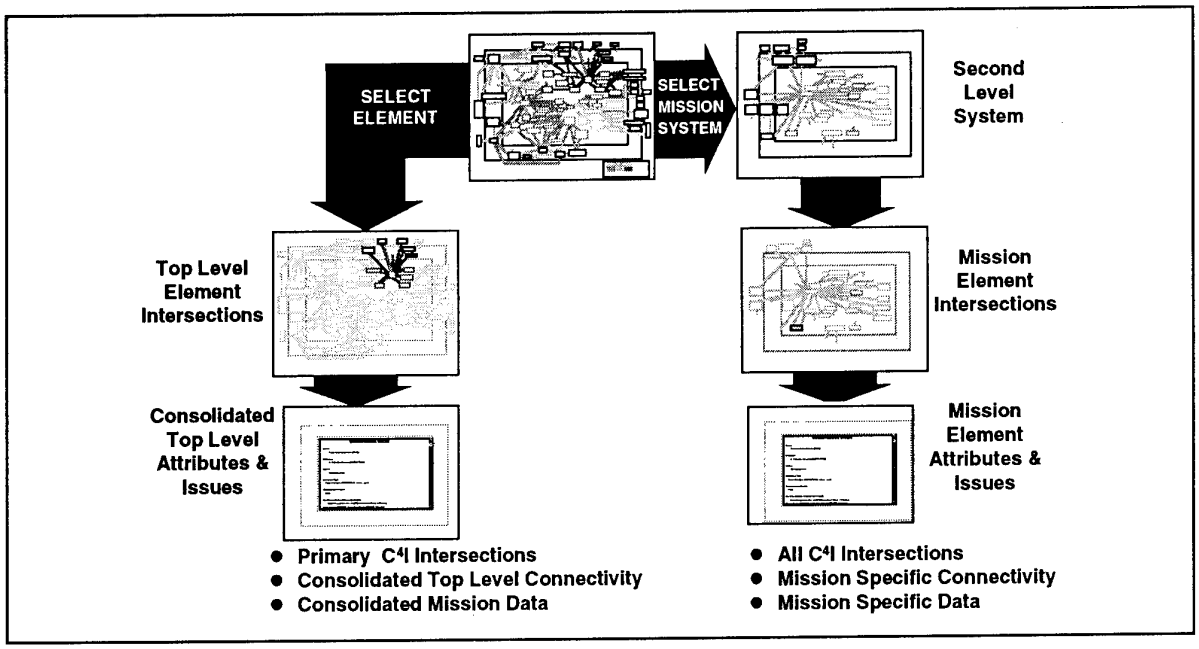


Figure 4-20. Horizon Data Base Retrieval

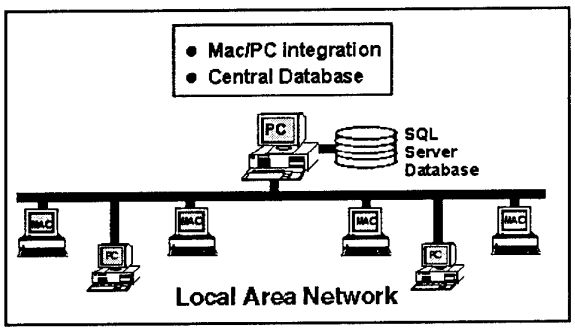


Figure 4-21. Horizon Link Configuration-Near Term

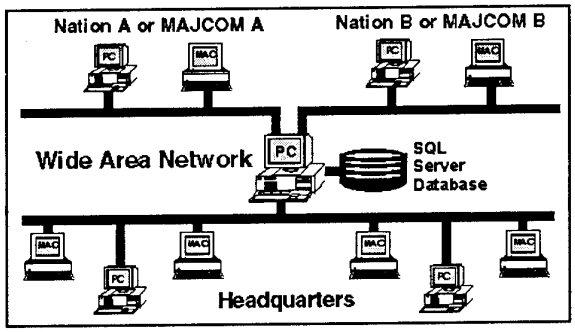


Figure 4-22. Possible Future Consideration

5. DERIVATIVE ANALYSES

The Horizon database may be extended into other areas or enterprises and may be used to support specific analyses, as shown in Figure 5-1. These are the extensions and analyses done to date based on the model, methodology, and results. The first major analysis done focused on the communications which support the information flow between nodes on the diagrams. The database can also support other analyses, such as AIS and operations, as illustrated in Figure 5-2. This section of the paper demonstrates how the Horizon Link databases have been used to support communications analyses.

The process combined Horizon and other communications data as shown in Figure 5-3. The reader may recognize the diagrams and interoperability tables on the left and center of the figure. The communications systems supporting USAF were identified and grouped, as shown in the left column of the inset on the right of Figure 5-3. The C4I elements, or nodes, are shown across the top, and the entries represent the type of information flow across the intersections; i.e., Data (D), Record Text (R), Electronic Mail (E), Voice (V), Fax (F), and Imagery (I) keyed to the communications systems in the left column. Thus, step 1 associates the communications systems with the C4I nodes (Figure 5-4).

The next step delves more deeply into the information flow intersection to associate communications systems with information flow lines; e.g., several communications lines or links may be employed to support the information flow between nodes. In an abstract sense, we have formed an X-Y plane, with X representing the communications systems (i.e., what systems), and Y representing the flow lines associated with a particular node set (i.e., who). Figure 5-5 illustrates this step.

A third dimension may be added; i.e., the Z axis, which can be used to represent the particular type of traffic and end terminals which are at the nodes and are supported by the communications systems to afford the desired or actual information flow. The segmented "poles" in Figure 5-6 may be analyzed on a planar basis to examine, for example, imagery flow within a mission area or throughout the enterprise.

Finally, as shown in step 4, Figure 5-7, a communications interoperability assessment may be made to examine the adequacy of the communications support to actual and required information flow and to identify issues that need to be resolved.

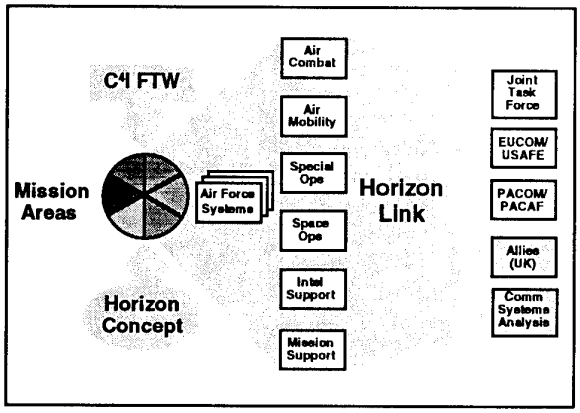


Figure 5-1. Horizon to Present

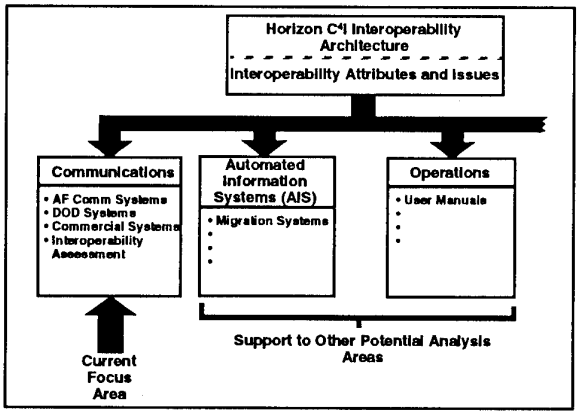


Figure 5-2. Possible Analyses

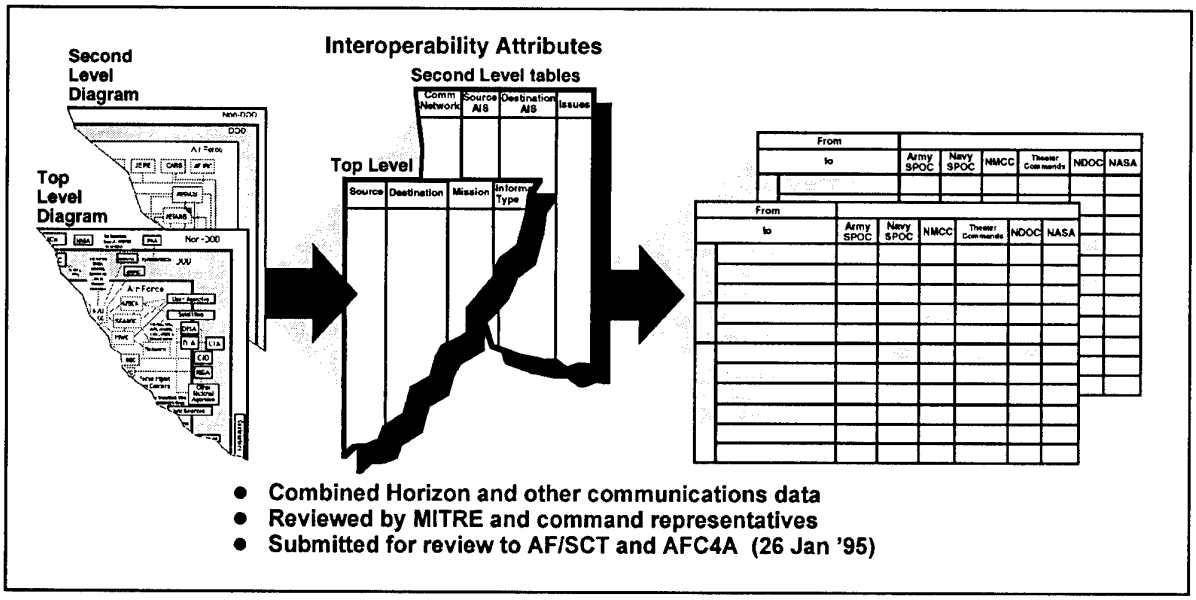


Figure 5-3. Horizon Communications Analysis Process

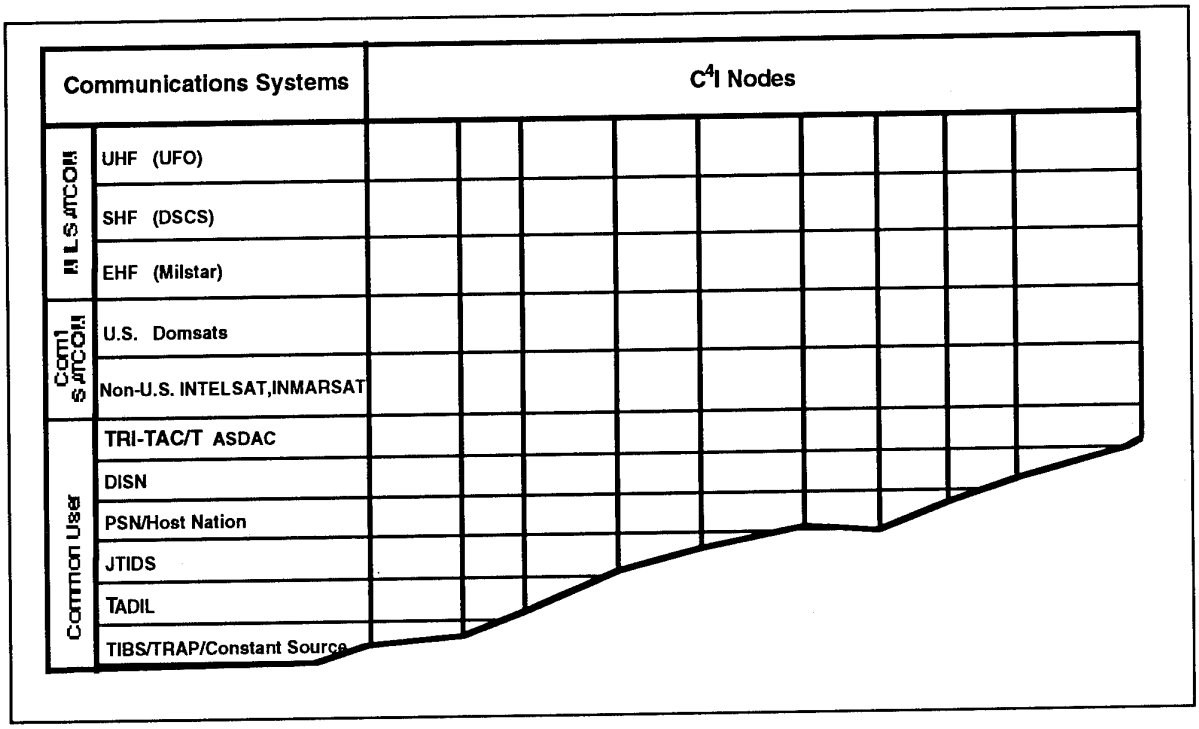


Figure 5-4. Step 1: Associating Communications Systems with C4I Nodes

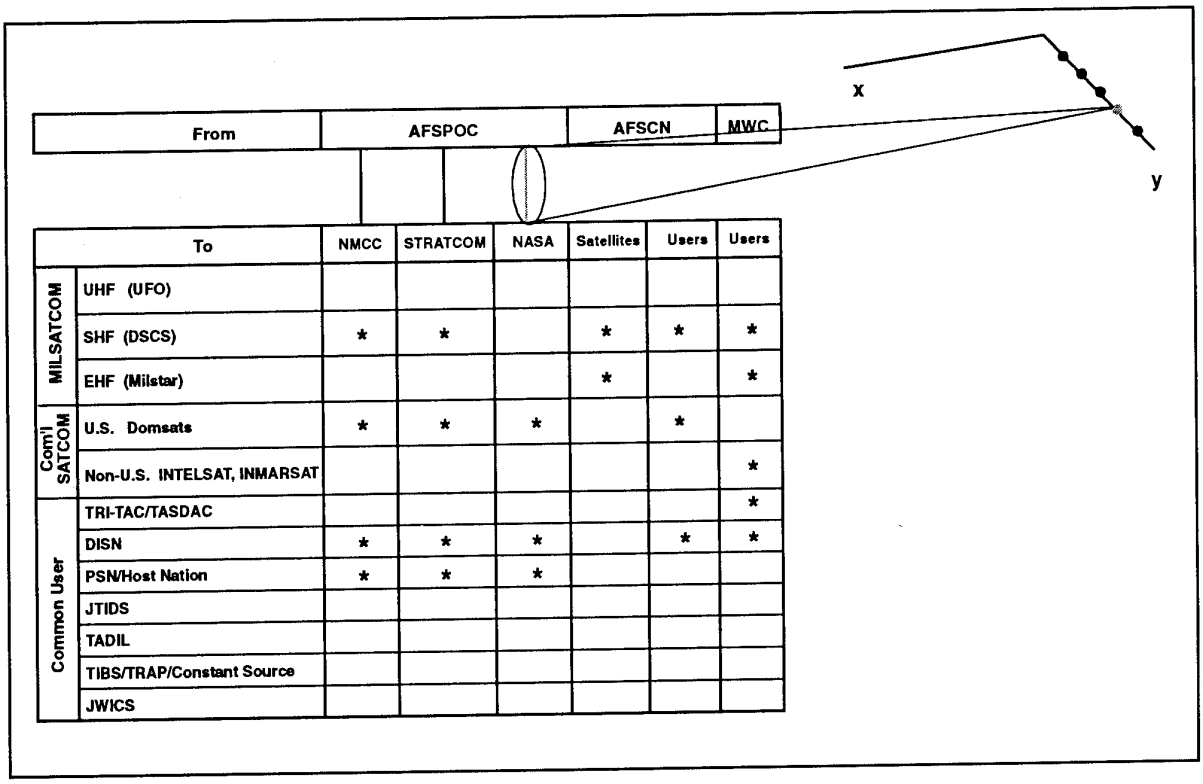


Figure 5-5. Step 2: Associating Communications Systems with Information Flow Lines

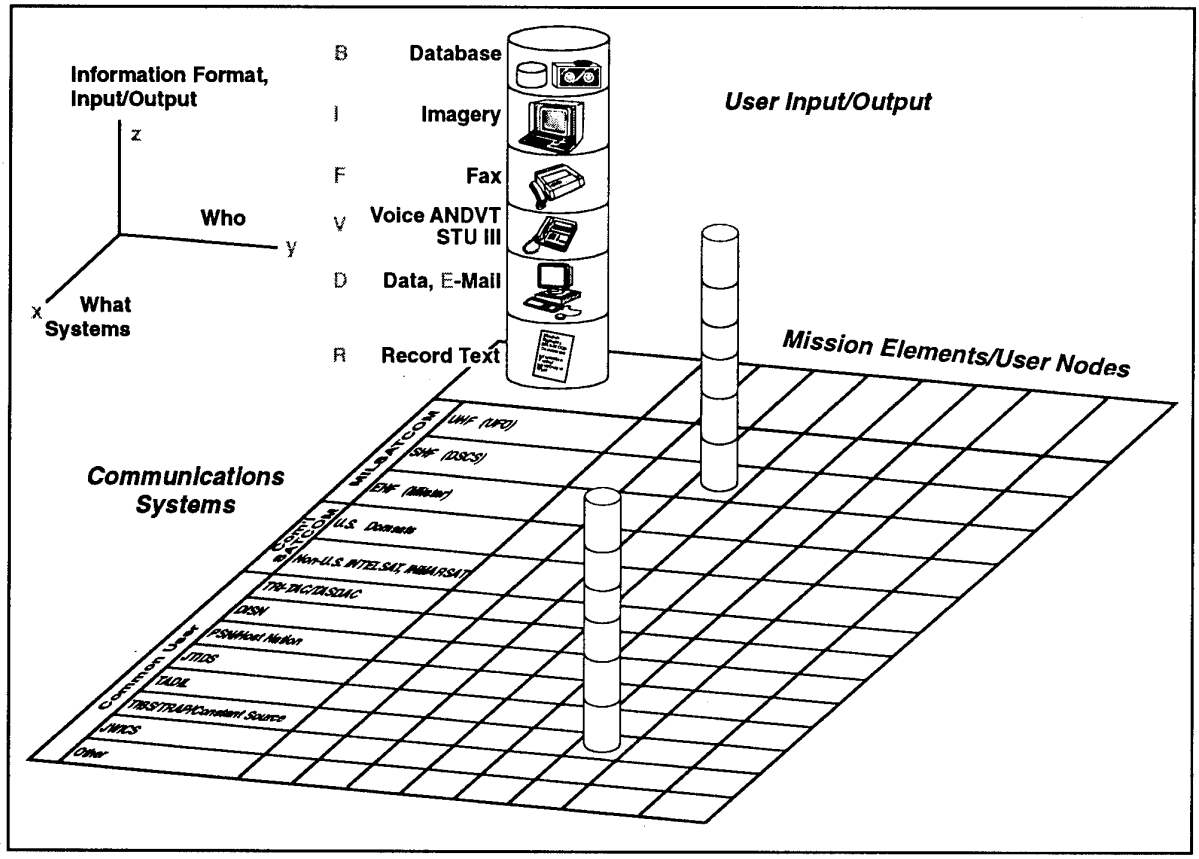
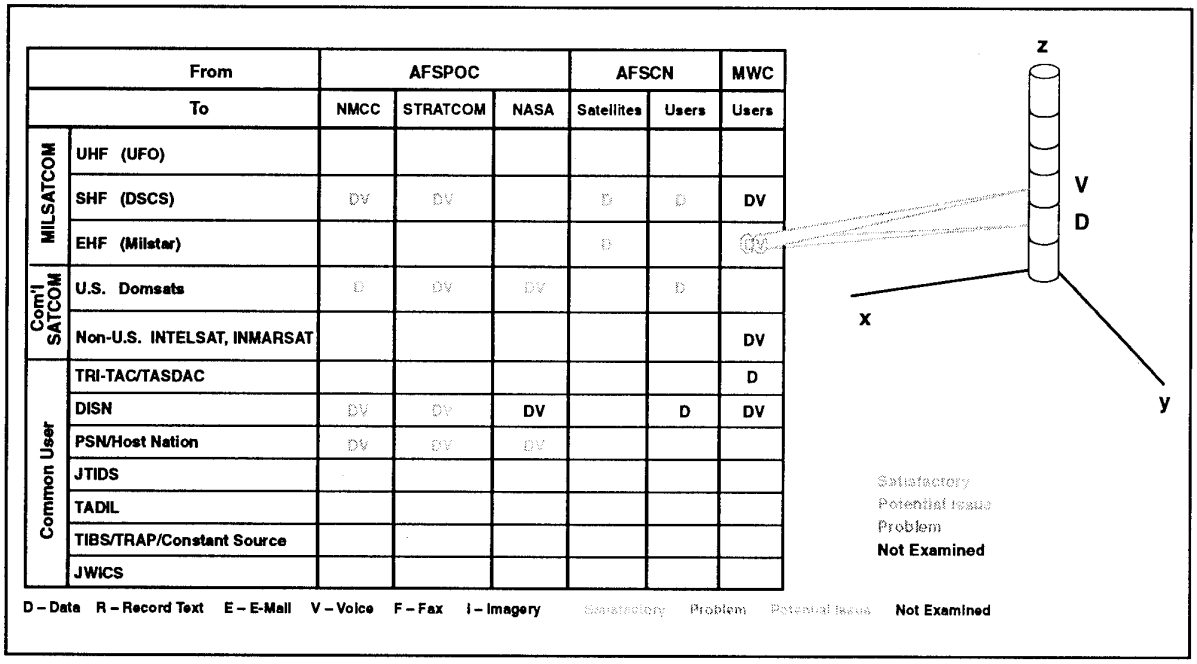


Figure 5-6. Communications Capabilities (a 3D Matrix)



From		AFSPOC			AFSCN		MWC
To		NMCC	STRATCOM	NASA	Satellites	Users	Users
MILSATCOM	UHF (UFO)						
	SHF (DSCS)	DV	DV		D	D	DV
	EHF (Milstar)				D		DV
Com'l SATCOM	U.S. Domsats	D	DV	DV		D	
	Non-U.S. INTELSAT, INMARSAT						DV
Common User	TRI-TAC/TASDAC						D
	DISN	DV	DV	DV		D	DV
	PSN/Host Nation	DV	DV	DV			
	JTIDS						
	TADIL						
	TIBS/TRAP/Constant Source						
	JWICS						

D – Data R – Record Text E – E-Mail V – Voice F – Fax I – Imagery Satisfactory Problem Potential Issue Not Examined

Figure 5-7. Step 4: Interoperability Assessment

6 A JOINT SCENARIO RELEVANT TO NATO

In order to illustrate the manner in which the Horizon C4I interoperability architecture management process may be extended to other mission areas and Command structures, we have selected a deployed Joint Task Force (JTF) scenario. Using the portrayal concepts developed in Section 4, the model is adapted to the deployed JTF applications by making the C4I elements which comprise the JTF the center of the diagram, as illustrated in the framework of Figure 6-1. The reader should notice that the inner boarder surrounding the C4I elements of the JTF is allocated to rear area or in-garrison support, while the outer boarder is reserved for non-defense interfaces. In a NATO-combined force scenario, this area could just as easily be devoted to national or top level NATO elements.

Following the methodology, boundaries are established for the major missions or forces which make up the JTF. Following guidance in references for unified and joint operations, the force elements and their boundaries may be identified as shown in Figure 6-2. Because Joint Task Forces may be assembled for a variety of missions which can include peace-keeping, humanitarian/relief operations, crisis management, regional conflict, etc.; the purpose of the JTF must be defined, so that its precise make-up may be portrayed in the model.

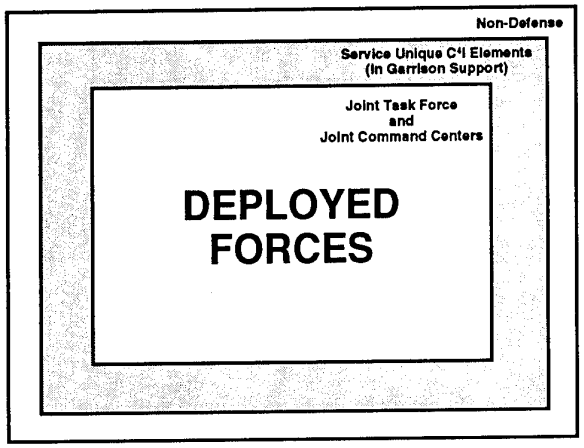


Figure 6-1. Model for Generic TLD for Joint Force Environment

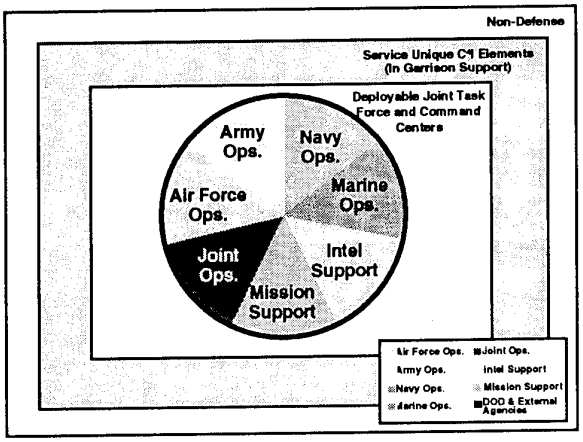


Figure 6-2. Operations and Support Areas

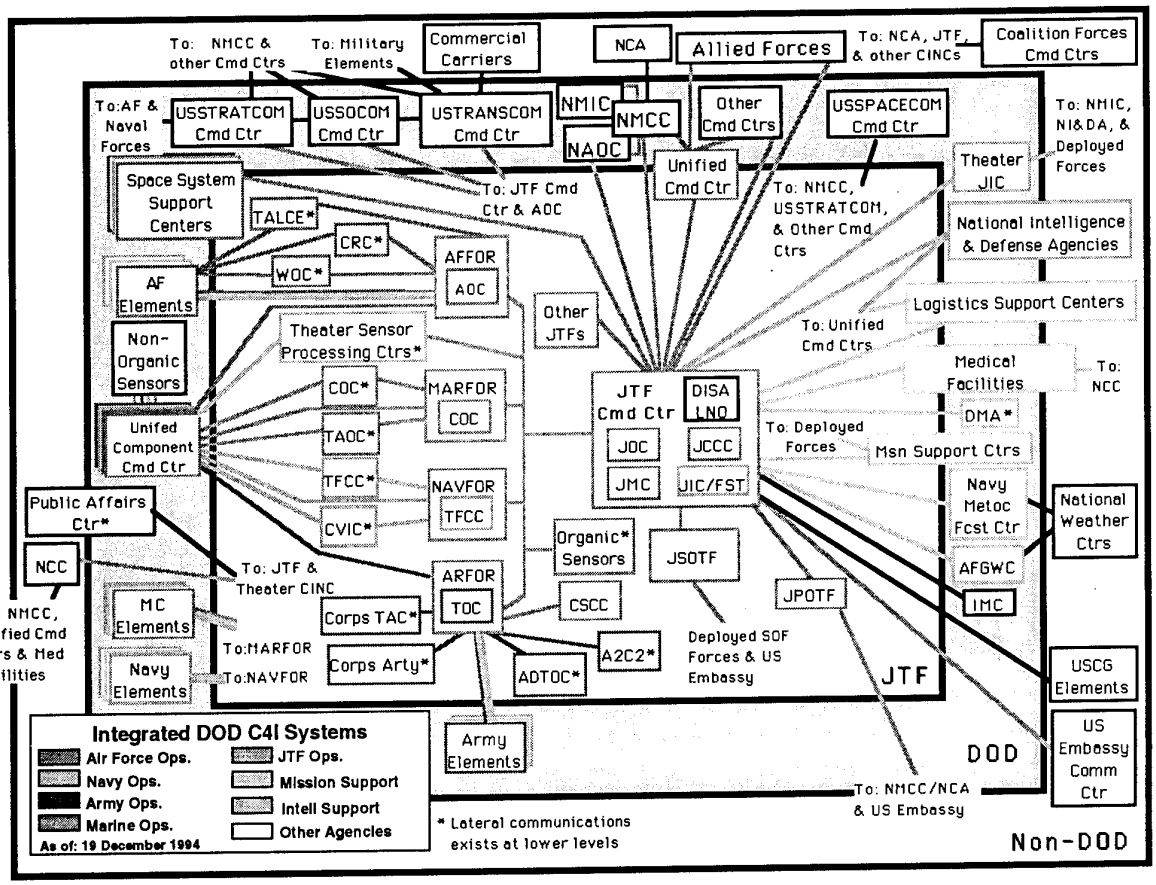


Figure 6-3. Top Level Diagram

For purposes of illustration here, the mission of the JTF is to ensure victory in a regional conflict. The nominal levels of the force elements are therefore:

- An Army Corps
- A Navy Carrier Battle Group
- A Marine Expeditionary and Amphibious Force
- A "Numbered" Air Force
- A Joint Special Operations Task Force

Applying the diagramming techniques described in Section 4, the Top Level JTF diagram is developed. The result of this phase of the effort is portrayed in Figure 6-3. Information flow tables may then be developed to describe the information flow and surface issues. (These are not included here in the interest of brevity.)

At the second level, the diagrams feature a particular segment of the wheel of Figure 6-2. Thus, in the case of the JTF illustration, there will be 7 second-level diagrams in the style of Figure 4-9 shown earlier. The supporting interoperability attributes tables, with contents similar to that illustrated in Figure 4-15, are formulated next.

The foregoing products: Top and Second Level Diagrams and the supporting interoperability attributes become the database in the Fox Pro-based Horizon Link tool. These data can be applied in force planning, identification, and resolution of interoperability issues at both the mission and system level, specialized analyses such as the communications analysis discussed earlier or operations analysis.

The JTF portrayal, C⁴I architecture, database, and tool may be extended to the combined force, multi-mission environment in which NATO finds itself in this era following the end of the Cold War.

7. CONCLUSION

"The history of command can thus be understood in terms of a race between the demand for information and the ability of command systems to meet it."1 Applying the Horizon methodology described in this paper, supported by the Horizon Link tool can help us move toward the level of C⁴I interoperability needed for effective interaction of forces to achieve mission goals.

The United States Air Force C⁴I Horizon is the concept of providing the warfighter with responsive, advanced C⁴I systems services. The Horizon model, methodology, and tool takes C⁴I for the Warrior, other United States Department of Defense Guidance and International Standards as the impetus for both a long-range C⁴I planning process, as well as a short-term interoperability issue identification and resolution process. The long-range process codifies existing C⁴I modeling efforts as they feed requirements definition, system design, acquisition, or prototype builds, testing, interoperability certification, and fielding of C⁴I systems for joint use. The short-term process, supported by the Horizon Link tool, examines a manageable set of critical C⁴I nodes and links that represent the DOD mission and support areas. Interoperability issues that surface from near-term assessments of the information flow across those area boundaries are addressed by an architecture steering group chartered to resolve deficiencies.

Changes in missions, their needs, and insertion of emerging technologies are fed back into the process. The result is a high degree of confidence in interoperability even across different mission areas.

The benefits of the C⁴I architecture management process described here derive from its clearly defining a set of system and mission boundaries and responsibilities, while allowing design freedom within mission systems. It identifies a single organization to manage and direct the overall C⁴I architecture. It provides a common top level portrayal of C⁴I interoperability for commanders and staff to understand and discuss parameters and issues, a tool to catalog and define systems and issues, and a forum to discuss, assign, and resolve issues in a joint or combined environment. The process can be extended to NATO.

8. REFERENCES - (AGARD)

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CJCS MOP 50 (revision) Mission Area Set, March 1993.

C³ architecture for JTF headquarters (validated), DISA JIEO report 8302, July 1992.

9. ACKNOWLEDGMENTS

The authors wish to acknowledge the pioneering work accomplished by the HQ USAF SCT staff. Special thanks also go to Messrs. Beamer, Beckner, and Brandon of The MITRE Corporation for their ideas and material contributions which made this paper possible.

1 Van Creveld, Martin L., "Command in War", Harvard University Press, (ISBN 0 674 144414).

10. GLOSSARY

A2C2	Army Airspace Command and Control Element
ABCCC	Airborne Battlefield Command and Control Center
ADC	Air Defense Center
ADOC	Air Defense Operations Center
ADTOC	Air Defense Tactical Operations Center
AFAC	Airborne Forward Air Controller
AFFOR	Air Force Forces
AFIWC	Air Force Information Warfare Command
AFMC	Air Force Materiel Command
AFSCN	Air Force Satellite Control Network
AFSOC	Air Force Special Operations Command
AFSPOC	Air Force Space Command Operations Center
AIA	Air Force Intelligence Agency
AMCC	Air Mobility Control Center
AME	Air Mobility Element
AOC	Air Operations Center
ARFOR	Army Forces
AWACS	Airborne Warning and Control Center
CIO	Central Imagery Office
COC	Command Operations Center
CRC	Control and Reporting Center
CSCC	Corps Support Command Center
CVIC	Aircraft Carrier Information Center
DISA	Defense Information Systems Agency
DMA	Defense Mapping Agency
FACP	Forward Air Control Post

GPMC	Global Patient Movement Center
ITO	Integrated Tasking Order
IWSM	Integrated Weapon System Management
JCCC	Joint Communications Control Center
JIC/FST	Joint Intelligence Center/Field Support Team
JICTRANS	Joint Intelligence Center, Transportation Command
JMC	Joint Movement Center
JOC	Joint Operations Center
JPOTF	Joint Psychological Operations Task Force
JSTARS	Joint Surveillance Target Attack Radar System
LCC	Launch Control Center
MARFOR	Commander, Marine Forces
MSF	Medical Support Facilities
MTF	Medical Treatment Facilities
MWC	Missile Warning Center
NAIC	National Air Intelligence Center
NAVFOR	Commander, Naval Forces
NMCC	National Military Command Center
OSC	Operations Support Center
RAMCC	Regional Air Mobility Coordination Center
ROCC	Region Operations Control Center
SOC	Special Operations Command (Theater)
SOCC	Sector Operations Control Center
SOF	Special Operations Forces
SOW	Special Operations Wing
SPADOC	Space Defense Operations Center
TACC	Tanker Airlift Control Center
TACP	Tactical Air Control Party
TALCE	Tanker Airlift Control Element
TAOC	Tactical Air Operations Center
TFCC	Tactical Flag Command Center
TMO	Transportation Management Offices
TOC	Tactical Operations Center
USSTRATCOM	U.S. Transportation Command
USTC	U.S. Transportation Command
WOC	Wing Operations Center
Wx	Weather

OPERATIONAL EFFECTIVENESS THROUGH INTEROPERABILITY

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SUMMARY

The increasing use of joint service, coalition forces to support modern warfare continues to magnify the importance of superior and flexible tactical command, control, communications, and intelligence (C^3I) systems. Interoperability has become a commonly identified key component in the success of this modern warfare. In this context, interoperability can be defined as the capability for two or more C^3I systems to share and manage common information to maximize the operational effectiveness of the combined force. Examples of common interoperability problems experienced during a number of military operations and exercises are described. Potential short and long term interoperability solutions, particularly in the areas of data communication, data fusion, and data management are presented.

1 INTRODUCTION

With the continuing reduction of conventional forces, the successful conduct of national and regional defense and military campaigns relies increasingly heavily on the force multiplier advantages of tactical C^3I mission systems. Key to this success is the ability to deploy and maneuver flexible forces employing technically superior C^3I systems. With the decreasing expectation of massive force confrontation and the increasing need for coalition forces to stabilize and resolve regional conflicts, C^3I systems must continue to focus on interoperability as a necessity of modern warfare.

The acquisition of C^3I systems by different services and different countries occurs relatively independently. These systems often provide narrowly focused capabilities for stand-alone or limited group operations. Operation Desert Shield/Desert Storm highlighted existing deficiencies in mission systems interoperability. And still, several years later, similar problems plague Operation Deny Flight. Today's systems employ a collection of heterogeneous data link standards inconsistently applied among services and nations. Interoperability is not only a problem of the past. Despite significant technological improvements, or perhaps as a direct result of these improvements, interoperability remains an enduring issue which challenges current and future mission system effectiveness.

The latest technology in remote sensing, aerial and space observation, intelligence, and communications magnifies the significance of interoperability to operational effectiveness. Information abounds from numerous sources. And yet the challenge remains to provide the highest quality information, at the right place, at the right time, to effectively accomplish the operational mission. A common air, surface, and subsurface surveillance picture, devoid of confusing and conflicting data, is needed to support complex system capabilities.

But the fiscal realities of declining budgets continue to challenge progress in interoperability. The life cycles of existing systems are being prolonged to minimize defense spending. With this extension comes the need to continue to improve interoperability among these existing systems. Furthermore, the deployment of new technologies adds a whole new layer of complexity to the interoperability issue. Many of the most modern systems were designed to facilitate interoperability with other modern systems. And so this small subset of recently developed systems operate relatively well among themselves. But these new capabilities do not address the lingering existence of the older systems which continue to provide the backbone of modern C^3I mission systems. The older, existing systems continue to struggle to operate effectively together and the challenges increase as we try to bridge the older systems with the new.

2 INTEROPERABILITY DEFINITION

The term interoperability is used in many different contexts and with many different interpretations. In Joint Publication 1-02, the United States (U.S.) Department of Defense (DoD) Dictionary of Military and Related Terms defines interoperability as "the condition achieved among communications-electronics systems or items of communications-electronics equipment when information or services can be exchanged directly and satisfactorily between them and/or their users." In the context of interoperability among C^3I systems to support joint and combined military force structures, this definition must be expanded to address the operational capabilities and benefits which are achieved by such an exchange of data. In the joint service and multinational arena, interoperability provides the capability for two or more systems to share and manage common information, derived from diversified sources, to maximize the operational effectiveness of each system and the collective effectiveness of the combined force.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C^3I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

Interoperability requires communication capabilities to provide for the timely distribution of ground-based, airborne, and space-based active and passive sensor data. This data distribution should include all joint force participants for whom this data is necessary to support the defined operational mission objectives. The C^3I systems which support these forces should evaluate and combine all of the available data to maintain and provide to the users the highest quality information. Data conflicts and inconsistencies must be addressed in order to provide an unambiguous and effective user presentation.

Figure 1 depicts a conceptual architecture which embodies the many components, or "layers," necessary to achieve operational interoperability. Communication equipment, such as radios, telephones, modems, encryption devices, in conjunction with communication protocols, provides the ability to transfer data. Message formats and standards for message processing provide for consistent interpretation of exchanged data. Data processing and data management, including registration, correlation, fusion, and conflict processing, in conjunction with system doctrine, are used to develop the highest quality information. Finally, an effective presentation of this high-quality information allows the C^3I operators to successfully execute the operational mission. It is at this point that full interoperability has been achieved.

3 OPERATIONAL EXPERIENCES

Our experience in working with the U.S. military services to solve interoperability issues during operational missions, as well as our experience in developing and deploying unique prototype data link "gateway" or "buffer/translator" systems for military exercises and demonstrations, provide continuing evidence of, and insight into, the interoperability limitations of existing C^3I systems. It is from this perspective that common interoperability problems can be identified and described. During these operational missions and exercises, prototype capabilities which improve interoperability have also been demonstrated. These experiences provide a unique perspective from which potential interoperability solutions can be identified. In addition, our role in the acquisition and development of C^3I systems which successfully address some of these common interoperability issues lends further support to the proposed solutions.

3.1 Operation Desert Shield/Desert Storm

During Operation Desert Shield/Desert Storm, a multinational force, comprised of NATO and allied forces, was established in response to the Iraqi invasion of Kuwait. The joint force included Army, Air Force, Navy, and Marine personnel, and combined ground, air, sea, and space-based resources to accomplish the common mission. During this operation, MITRE contributed technical expertise necessary to design an effective data communication architecture to connect the many participant C^3I systems and to resolve data link configuration issues. Additionally, MITRE deployed a prototype Joint Tactical Information Distribution System (JTIDS) display system, used by the self-defense officer on-board the pre-production Joint Surveillance Target Attack Radar System (STARS) aircraft, to provide situational awareness. MITRE personnel were deployed in-theater to assist in the real-time resolution of operational problems.

3.2 Operation Deny Flight

Operation Deny Flight is an ongoing joint NATO and allied operation established to support the United Nations (UN) humanitarian mission and to enforce the military no-fly zone in the former Soviet state of Yugoslavia. MITRE has been consulted by field units deployed within the theater of operation to assist in alleviating data link connectivity and throughput problems between the services and among allied nations.

3.3 Joint Air Defense Operation/Joint Engagement Zone (JADO/JEZ) Program

The JADO/JEZ test and evaluation program is conducted by the U.S. Army, Air Force, Marines, and Navy to investigate and evaluate the concept of combined air defense operation, experimenting with hostile aircraft identification and engagement techniques and procedures. This program is conducted using system modeling and simulation followed by field test exercises. MITRE has provided engineering expertise necessary to design the data link network architecture used to support this exercise. In addition, MITRE provided a prototype "buffer/translator" system which translated and forwarded data between Tactical Digital Information Link (TADIL) J, Interim JTIDS Message Specification (IJMS), and TADIL B networks. The prototype system also provided a composite display, derived from data from all of these networks, which was unavailable together in any of the C^3I mission systems.

3.4 Roving Sands Exercises

Roving Sands is a joint U.S. field exercise conducted annually to provide realistic joint service training in theater air defense operations. During the 1994 exercise, MITRE provided a prototype "buffer/translator" system which translated and forwarded data between TADIL J, IJMS, and TADIL B networks, connecting Army missile batteries to Air Force and Navy airborne assets. During the most recent 1995 exercise, theater ballistic missile defense concepts were demonstrated and evaluated. In support of this exercise, MITRE provided a prototype capability to receive theater ballistic missile launch and impact point

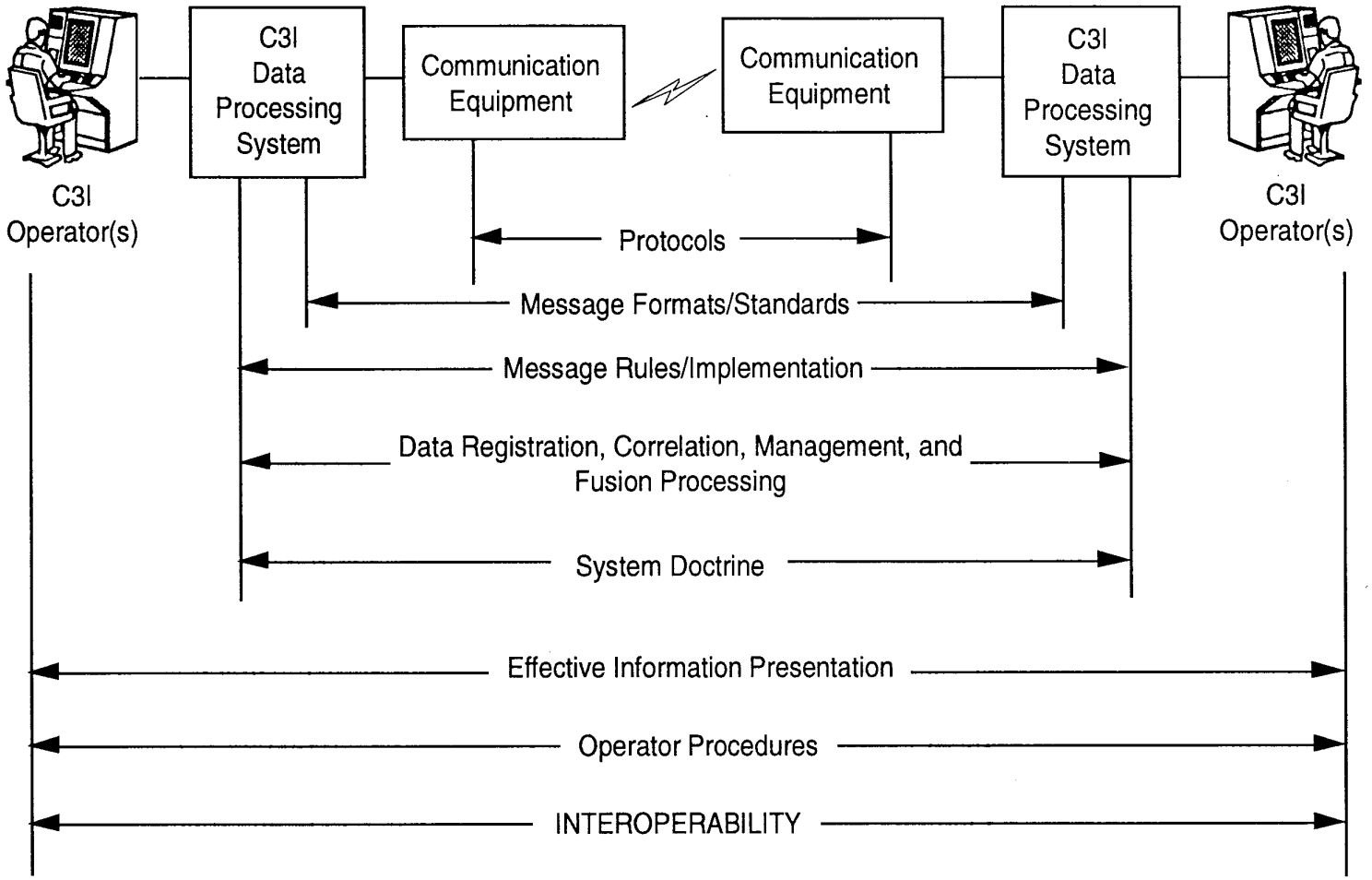


Figure 1. Conceptual Interoperability Architecture

information from missile tracking systems and intelligence sources, and distribute this information to C³I mission systems via JTIDS. The prototype system also translated and forwarded surveillance information from the JTIDS network to several TADIL B link participants. In addition, a prototype data fusion capability was provided to investigate the operational benefits which could be achieved with such a capability.

3.5 Theater Air Defense/Operational Concept Demonstrations

This series of demonstrations has been undertaken to verify the capabilities of existing C³I systems to detect, track, and report launch and impact points for theater ballistic missiles. In addition, past demonstrations have examined the capabilities available to locate, identify, track, and attack theater ballistic missile transporter-erector-launchers. MITRE has deployed prototype systems to translate and forward intelligence data onto the JTIDS network. In addition, the prototype system provided a composite situation display derived from tactical and intelligence data.

4 DEMONSTRATED INTEROPERABILITY PROBLEMS

Despite changing technologies and the evolution and development of C³I systems, interoperability remains an enduring issue. A fairly common set of serious interoperability problems was experienced at all of the above operational missions and exercises. And despite the "lessons learned" documented as a result of each, these problems continue to exist.

In support of these types of operations, numerous data links are established within the theater of operation. Figure 2 depicts a generic data link topology, similar in concept to those used in these operations, designed to provide interoperability. Numerous data links are combined in standard and non-standard configurations. Some of the most common tactical data link standards in use include JTIDS (TADIL J (Link 16)/IJMS), TADIL A (Link 11A), TADIL B (Link 11B), ATDL-1, Improved Data Modem (IDM), Link 14, Link 1, and TADIL C (Link 4). In addition, the intelligence community has defined another set of unique data link message standards. These include the Tactical Information Broadcast Service (TIBS), Tactical Receiver and Related Applications (TRAP), and Tactical Data Information Exchange System (TADIXS).

Within these topologies, stand-alone C³I mission systems attempt to participate in joint operations, without the benefit of shared information. Other C³I mission systems employ data links which are incompatible with those of their counterparts. Translation between different data link standards is available for only a small subset of C³I systems. Unique "buffer/translators" and "gateways" may facilitate communication but do not address the data management, data fusion, and display processing necessary to make effective operational use of the available data. Furthermore, the "buffer/translator" architecture introduces a potentially critical single point of failure. Communication bottlenecks, delays, and data loss often result from the different data link capacities on these heterogeneous networks.

To further complicate the communication problems, C³I systems do not consistently and correctly implement the defined data link message standards. The message standards are an evolving set of message formats and implementation rules. In order to maintain interoperability, all systems on the network must adhere to the same requirements. However, many systems do not continue to update their data link capabilities as the standards evolve. And in many cases, different versions of the same data link standard are not compatible. For example, the well-documented lack of interoperability between IJMS and TADIL J, both part of a JTIDS network, clearly illustrates this problem. Not only are IJMS and TADIL J not compatible, incompatibilities exist between different versions of JTIDS terminals and different releases of the TADIL J message standard. Many systems choose to selectively implement the specified message processing requirements. Although from a narrow perspective, this decision may be reached for a valid reason, it usually results in data conflicts, an incomplete or inconsistent surveillance picture, and operational limitations when operating with other systems that expect each network participant to interact in an established, predictable manner.

Each system in a combined theater of operation contributes a subset of the information necessary to conduct a successful military campaign. Collectively, these systems have the potential to develop the most complete understanding of the operational situation within the area of interest. Unfortunately, as data communication is effectively achieved, new problems are exposed. The abundance of data often adds confusion, rather than adding useful information. Duplicate data, erroneous data, conflicting data, and gaps in data may result in an incorrect, incomplete, or inconsistent surveillance picture among C³I systems. The overlapping coverage of different sensors provides redundant data at varying levels of fidelity. Most of the existing C³I systems do not have any automated capability to perform data fusion to address these issues. Duplicate and conflicting data complicate operator interpretation of the available information. Furthermore, limited and inconsistent data management is performed by and among the existing C³I systems. C³I system capacities can easily be exceeded and data potentially lost as a result of overlapping data received from multiple data links. Different track numbering

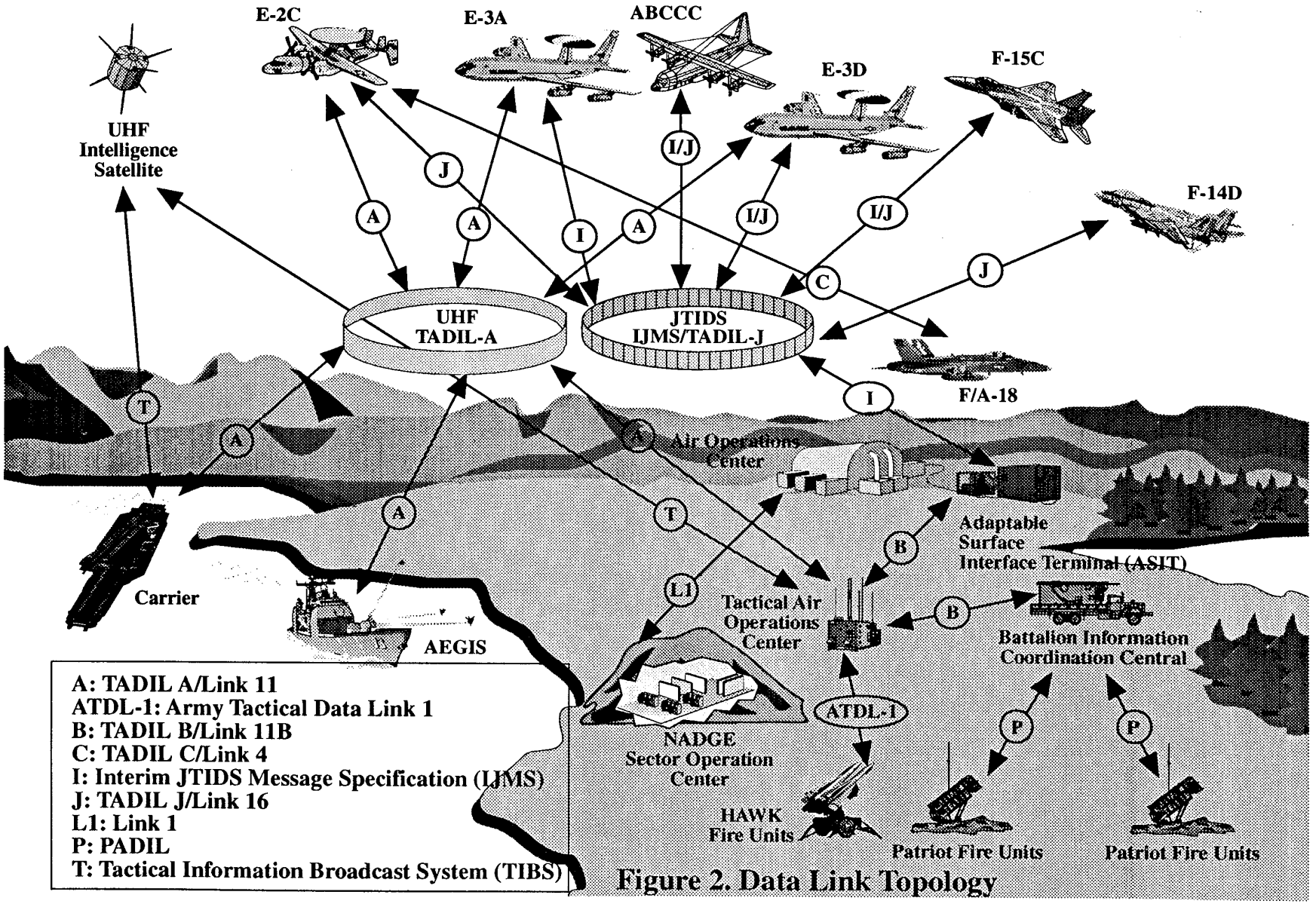


Figure 2. Data Link Topology

schemes and the lack of track correlation and track number translation hinder operator interpretation of available data for the same target. Duplicate and dual track data results from inconsistent and selective application of reporting responsibility rules by C^3I systems. Unresolved reporting responsibility conflicts and track number conflicts result in incorrect or inconsistent target data between systems, including significant target attributes such as target identification. Information ambiguity results from unresolved data conflicts between C^3I systems. With these ambiguities, the potential for fratricide and undetected hostile targets significantly increases.

5 INTEROPERABILITY SOLUTIONS

The multifaceted solution to interoperability must address five key components: operational roles and missions, data communication, data fusion, data management, and composite data display. The remainder of this paper will focus on the data communication, data fusion, and data management aspects of the interoperability solution, based on our experiences in operations, acquisition, and development.

5.1 Data Communication

Successful communication requires the use of a common "language", including clearly defined "terms" which can be consistently and correctly interpreted by all. Successful data communication requires not only compatible communication equipment and communication medium, but also a standardized set of data messages and message processing rules through which information can be conveyed. Over time, the U.S. DoD and the international community have defined many sets of standard data communication "languages." These different standards have been applied to narrowly focused individual applications, in different theaters of operation, without significant regard to the potential needs of other services and nations. Though many of these standards are used to convey similar types of surveillance information, the unique physical interfaces, message standards, and protocols prevent interoperability between the standards.

In the long term, the operational capabilities of each of the data communication standards currently employed or under development need to be reviewed. This review should consider the current capabilities of each standard, as well as its ability to support communication growth requirements. This review should also address other factors such as cost, availability, long term supportability, and releasability. The anticipated operational requirements of the joint services and allied nations, both in the near term and the long term, must be considered in the context of the available capabilities. Clearly this will require extensive, complex, cooperative discussions among the various services of all allied nations. If joint and combined operations are to succeed, a smaller set of standards should be selected for continuing support. In evaluating and identifying the appropriate set of communication standards, the military community should also consider the substantial advances underway in the commercial sector. Military protocols could potentially be embedded in evolving commercial data communication standards, taking maximum advantage of the potential benefits of the commercial communication infrastructure. Certainly, the uncoordinated development of additional new standards should be sharply curtailed, minimizing further development costs and maximizing the utility of the available data communication capabilities. Limiting the selection of data communication standards to a very small subset of those already in use would substantially reduce the incompatibilities which currently exist and greatly simplify the task of bridging the gaps between dissimilar systems.

A joint service effort of this type has already been initiated in the U.S. for tactical data links. In his 18 October 1994 letter to military department secretaries, directors of the defense agencies, and the Director of the Joint Staff, Assistant Secretary of Defense Emmett Paige, Jr. designated JTIDS/Link 16 as the U.S. DoD primary tactical data link for all service and defense agency command and control, intelligence, and weapon system applications. This policy decision was intended to reinforce the C^3I Common Data Link (CDL) policy of December 1991, requiring, to the maximum extent possible, that all information be disseminated through Link 16 to permit standardized, interoperable, data link support directly to the operator on the battlefield. Unfortunately, this policy statement does not address the needs of the international community. Nor does it address the continuing existence of older C^3I systems which cannot accommodate such a modification. Furthermore, the significant funding which would be required to comply with this policy is unlikely to be available. As a first step, this policy statement is significant. Although the solution begins here, a long term implementation plan will also be needed.

A transition of this type will have substantial technical and cost impact and will require many years to accomplish. For such a transition to occur, significant funding must be planned to accomplish the necessary modifications. In the current environment of declining defense budgets, priorities must be revised to accommodate these new requirements. It is also likely that some systems may never be able to participate in such a transition. Operational priorities will have to be established to identify those C^3I systems which are most critical in the tactical arena. Also, systems which are near the end of their life cycle may be bypassed in favor of newer or more capable systems. Although full

compliance may never be achieved, significant improvements could be anticipated.

For each data communication message standard defined and maintained for the purpose of interoperability, a process must be established to provide and enforce consistent interpretation of, and compliance with, the requirements of the standard. For some of the current standards, a subset of this process has been unsuccessfully attempted. For newly developed systems, formal testing is conducted to verify compliance with certain data link standards. Deficiencies identified during this testing are documented. However, the organizations involved in such testing exercise no influence over the operational community to limit the participation of non-compliant systems in the operational arena. Furthermore, compliance of each system is not always re-verified as the standards evolve. During Desert Storm, for example, a number of systems included in the data communication networks were never certified to comply with the existing data link standards. Others had been certified in accordance with a previous version of the applicable standard, but not the current standard. And for some standards, no formal certification verification is performed.

A formal, iterative standardization process should be established for each data communication standard which supports interoperability. This process could be characterized as a cradle to grave effort. A joint service, multinational organization must be empowered to maintain and enforce these standards. Such an organization could assess new user requirements, evaluate the capabilities of the current standards to meet these requirements, and assess the potential technical, cost, and schedule impact of approving a change to the applicable standard to incorporate the new requirements. In order to maintain and continue to improve interoperability, modifications to the applicable message standards should not be approved without first considering the necessary funding and developing a feasible, long term plan to upgrade all affected systems. This organization must continue to verify consistent compliance with each of the established standards, repeating the verification of each system after each approved modification to the standard. Most importantly, this organization must have the authority to enforce compliance and restrict operational participation based on documented performance limitations.

Even as the set of data communication standards is refined, capabilities will still be needed to bridge the gaps between dissimilar data links. A small number of systems include an organic capability to receive and process data from different types of data links. In the long term, an embedded capability of this type is highly preferable. Most systems, however, still require the use of an external "buffer/translator" or "gateway" system to translate and forward data between dissimilar data link standards. Unfortunately, a number of unique buffer/translator systems are being developed concurrently and independently through the efforts of both the government and industry.

MITRE has developed a prototype buffer/translator system called the Multi-link Translator and Display System (MTDS). This buffer/translator system has been successfully deployed at a number of operational missions and exercises, as described in Section 3. The MTDS is a transportable, proof-of-concept buffer/translator system based on commercial-off-the-shelf, workstation-based hardware, C++ software, and open system standards. It operates in an MS-DOS environment and interfaces with multiple tactical data links via software-controlled interface boards which process military standard protocols. The MTDS translates a subset of surveillance, intelligence, and management messages between IJMS, TADIL J, and TADIL B. The MTDS has a situation and tabular display and operator controls and alerts which can be used to display a composite surveillance picture and control and filter the exchange of information among the data links. The user interface capability of the MTDS has also been augmented to support track-level fusion related displays, as described in Section 5.2. The MTDS can record and play back messages received from the tactical data link interfaces.

The prototype MTDS buffer/translator system has been used to validate and demonstrate the significant improvements in interoperability which can be achieved. The MTDS has been used to resolve incompatibilities between data communication equipment, encryption methods, message standards and protocols, and data throughput bottlenecks.

In support of a long term transition to improve interoperability, buffer/translator systems could provide cost-effective solutions to interim incompatibility problems. However, a number of different non-standard buffer/translators could detract from the potential benefits. A "productized" buffer/translator system would offer the advantages of a standardized operational procedure, consistent capabilities, and improved supportability. The MTDS could provide a candidate design for such a "productized" solution.

5.2 Data Fusion

Tactical C^3I mission systems typically rely on inputs from multiple networks of distributed sensors and tracking systems. Track data from these multiple sources is then "merged" to provide a single surveillance picture. This surveillance picture is displayed to operational personnel to conduct and coordinate vital

mission activities such as early warning, target identification, weapons control, and airspace management and control.

In many C^3I systems, operators must merge track data manually. That is, when data for the same track is independently reported by more than one source, it is typically the responsibility of the operator to recognize and resolve the overlapping data situation. Some C^3I systems have begun to automate this process. Automatic track-to-track correlation allows track reports received with different track numbers to be correlated as the same target. For multiple track reports received with a common track number, and for correlated tracks received with different track numbers, a variety of "preferred source" approaches have been developed to combine the overlapping data for display. These approaches select the "best track" for display from the available data, based on ad hoc rules which are unique to each system. The selection of a "preferred source" is often based on the track position accuracy as indicated by the source reported track quality. The currently defined track quality measures are not based in rigorous analytical foundation and are often not reliable indicators of track accuracy. As a result, the most accurate track may not always be selected. Moreover, with this approach, gains in tracking performance that could be realized by combining multiple track estimates are lost. Typically, little is done to merge or combine track attributes from multiple sources that represents a single target. Using the "preferred source" approach, track attributes available from sources other than the "preferred source" may become unavailable or not readily available to the operator, potentially resulting in a degraded operational capability.

Two recent acquisition efforts undertaken by the USAF Electronic System Center (ESC), with system engineering support from MITRE, have demonstrated substantial progress in the data fusion arena. These air defense systems both rely on variations of the "preferred source" approach for data fusion, but also accommodate data from other sources to provide the most complete composite surveillance picture, based on all of the available data. The acquisition of a TADIL A capability for the Royal Thai Air Defense System (RTADS) in the late 1980's provided a successful solution for merging local track data derived from multiple ground-based radars and operator inputs with TADIL A track data received from external sources. In RTADS, the available multiple overlapping ground radar coverage significantly increased the probability of high quality, reliable local track data. When a local track established a reliable status as the result of regularly correlated radar reports, the local track data was processed as the "preferred source." However, track attributes available from the local data were supplemented by additional attributes potentially available from external sources, and all attributes were merged into a single system track representing the target. Extensive data management processing was provided to alleviate the potential data conflicts which could arise with this approach. The acquisition of the Iceland Air Defense System (IADS), still ongoing, provides a similar solution to this problem. The track management requirements for the IADS system are somewhat more complex as a result of the numerous and different data links which provide track data derived from external sources. The IADS system also implements a "preferred source" approach. The IADS situation display is primarily based on the data available from the "preferred source." However, data from each "remote" track which has correlated with the "preferred source" track is also available by selective operator request on both the situation and tabular displays.

While these acquisition efforts resulted in a much improved operational capability, the state-of-the-art in data fusion continues to advance. Modern track-level fusion methods address the same need to automatically process the abundance of available information from multiple sources. A number of track-to-track fusion experiments and prototype development efforts are underway both in the government and in industry. The evidence available thus far indicates that these methods have the potential to provide a more comprehensive, stable, quality surveillance picture.

Beginning in 1993, ESC has sponsored MITRE Mission Oriented Investigation and Experimentation (MOIE) projects in an effort to develop a fieldable prototype multisensor fusion, data link buffer/translator system. During the first year of theoretical study and analysis, three track-level fusion approaches were studied: Austere, Covariance Based, and Pseudo Measurement Reconstruction. In 1994, five candidate algorithms, based on these track-level fusion approaches, were evaluated for their performance potential, robustness, ease of implementation, and extensibility. The competing demands of near-term and long-term capabilities and considerations were evaluated, and a Covariance/Weighted Average, Normalized Statistical Distance Association (NSDA) algorithm was selected for implementation in a prototype track-fusion system. This algorithm optimally combines remote and fusion track state information using covariance data developed on the various tracks.

Using this covariance approach, a prototype fusion system was developed. The track-level fusion processor prototype was designed to accept track information from the MTDS tactical digital information data link buffer/translator prototype system described above. The fusion processor correlates and combines the remote track data received from the MTDS to develop fusion

tracks and generates fusion-related display and alert information. The 1994 fusion prototype performed its processing in non-real time, with a focus on improving kinematic performance. In 1995, the prototype has been enhanced to process tactical data in real time. In addition, the continuation of this MOIE project will add an identification fusion algorithm to the fusion processor. The selected algorithm approach is based on the Bayes' Theorem.

Commercial statistical analysis and spreadsheet software capabilities have been used to perform off-line quantitative performance analyses. Performance of the fusion tracker was evaluated against simulated data using Monte Carlo techniques. In addition, tactical data recorded by the MTDS at a variety of operational exercises, including those described in Section 3, above, has been used to support fusion algorithm performance assessment.

The performance of the fusion tracker was evaluated based on the accuracy and stability of the position, speed, and heading of constant velocity and maneuvering targets. The fusion tracker performed successfully against a range of simulation scenarios. Fusion tracks performed better than remote tracks in every measure investigated. Some improvements were incremental; many were substantial. The fusion tracker correctly combined multiple remote tracks that represented the same target and discriminated among closely spaced tracks that did not. The fusion tracker generated more accurate estimates of target kinematics against both constant velocity and maneuvering targets. The improvements were especially dramatic for velocity accuracy and stability. The improvements to maneuvering target tracking are also noteworthy because combined requirements for accuracy and stability place difficult and competing demands on a tracking system's design. These results would be particularly significant to critical air defense functions, such as weapons guidance, that depend on both accuracy and stability.

The performance of the fusion processor was also evaluated against operational exercise data recorded by the MTDS. Because kinematic truth data was unavailable on the vast majority of the targets, tracker accuracy was difficult to assess. However, demonstrated improvements in speed and heading stability for both constant velocity and maneuvering targets corroborated the simulation results. The detailed results of the performance assessments conducted for the fusion processor are documented in [3].

Other improvements demonstrated by the fusion tracker include track continuity and improved track attribute data. Simulation scenarios were demonstrated in which a target traversed through the adjacent surveillance volumes of three different remote tracking sources which did not have overlapping coverage. Each of the remote trackers maintained the track during one third of the scenario. The fusion tracker generated one track on the target throughout the entire scenario, including two small gaps in surveillance coverage from any of the remote sources. This marked improvement in track continuity could result in a significant decrease in track maintenance activities to be performed manually by surveillance operators. In addition, improved track continuity allows track attribute information to be retained throughout a scenario or operational mission, with less regard to varying track sources and track quality. Similar to the RTADS and IADS systems, the fusion processor also employed a simple but potentially powerful approach to managing track attribute data. Once the remote tracks were correlated, attributes provided by multiple sources were combined for display. For attributes available from more than one source, Boolean logic was used to combine the constituent data. This approach resulted in a more complete set of attribute data for the fusion track than for any of the individual remote tracks.

The fusion processor was successfully deployed at the 1995 Roving Sands exercise to provide a real-time display of fusion tracker data. Performance improvements achieved in laboratory experimentation were evaluated in this live operational environment.

Clearly, significant operational improvements can be achieved by incorporating data fusion capabilities in C^3I mission systems. The experimentation and demonstrations conducted in recent years validate the concept and quantify the potential performance improvements which might be expected from this type of capability. However, a significant amount of work remains to be accomplished. Track-level fusion has not yet been incorporated in existing, operational C^3I systems. Requirements for new systems and modifications to existing systems that rely on interoperability should address data fusion as a significant capability which will maximize operator effectiveness. The results achieved by the fusion prototype in exercises such as Roving Sands could be used to help define feasible, practical requirements in the track data fusion area.

5.3 Data Management

Data fusion begins to address the complications which result from the abundance of data which can be available in complex networks comprised of different data links. Additional data management procedures and capabilities are equally imperative to further control and resolve data conflicts.

The variety of track numbering schemes implemented by the different data links causes innumerable difficulties in managing the surveillance picture. Some

of the common formats include four octal digits, five octal digits, and two alphanumerics followed by three octal digits. Some of the data links provide a message type which relates two different track numbers, in different formats, to the same track. Unfortunately, without an automated correlation capability, most systems do not have the ability to recognize such a relationship and generate this type of message. Furthermore, most systems do not have the ability to process such a message on receipt to automatically manage available overlapping data. In the absence of a track-level fusion capability, or at least an automatic track-to-track correlation capability, most systems process tracks reported with different track numbers as different tracks. As a result, an operator may view several "superimposed" tracks representing each actual target. For tracks reported on the same data link, or at least reported using the same track number format, an operator may have the capability to manually identify a dual track condition and resolve the condition by voice coordination. In many cases, "buffer/translator" or "gateway" systems further complicate this problem by translating track numbers initiated by the message source to a format required by the other end system, further obscuring to the user of the end system the relationship between the two different track numbers. These dual track number problems will only be resolved as track-to-track correlation, data fusion, and track-level fusion capabilities become more available in C^3I systems. Until then, the potential for overlapping track data will require extensive operator interaction to maintain an effective situation display presentation.

The system capacity of any C^3I system can easily be exceeded in an environment which includes multiple data links providing unmanaged or poorly managed reporting of overlapping track data. In designing the communication architecture to be implemented in support of an operational mission, the capacities of the participating systems must be considered. However, additional tools must be provided to manage the volume of data received by a C^3I system, especially in areas of multiple overlapping coverage and high target density. One of the most common tools implemented by many C^3I systems is a message filtering capability, based on factors such as geography, identity, simulation status, forcetell and emergency conditions. This capability allows C^3I systems to prioritize data processing based on areas of interest and the defined operational mission, rather than accepting data on a "first come first serve" basis. Display filters also allow operators to focus on the data of most value to the operational scenario. Attention displays should be provided to alert operators that the system capacity is being approached or has been exceeded. These types of alerts allow the operator to utilize the available tools to more effectively select and manage the data needed to perform the operational mission and that which can be discarded.

Another significant issue in the management of track data is the incorrect, incomplete, and inconsistent interpretation of track reporting responsibility rules by different C^3I systems. Some systems intentionally choose not to implement reporting responsibility processing. In an environment where each system is dependent on all other systems for adhering to a common track reporting approach, such a decision can contribute enormous confusion to a complex surveillance picture. Duplicate and dual track conditions will occur with increasing frequency. Significant position instability may be observed as a result of the chaotic track reporting. Track attributes, such as identification, raid size, platform type, and mission, may fluctuate between two or more entirely different sets of characteristics. In recent joint service experiments, reporting responsibility conflicts were demonstrated to significantly detract from the ability to correctly and consistently identify hostile targets for engagement. In such a situation, a system known not to correctly implement all reporting responsibility rules should not be allowed to transmit data on the network. Organizations which maintain and enforce compliance with the data link standards, as discussed above, should clearly identify these issues to the operational community so that they may be considered in the communication architecture used to support an operational mission.

The data management capability must also support the resolution of data conflicts for targets derived from multiple sources. Gross distance checks are typically used to evaluate the target positions reported by each source. If different targets are erroneously reported with the same track number, a duplicate track number condition should be reported to the operator for resolution. A dual track number condition may also be reported to the operator if it has been received from a data link message or detected by a track-to-track correlation capability. Many of the data link standards explicitly define detailed rules for identifying and resolving identity conflicts. Similarly, Identification Friend or Foe (IFF) conflicts may also be identified and resolved, based on specified message implementations.

To achieve an operationally useful capability, data management is not optional. Adding communication to increase the amount of available data is of little use unless the data can be managed effectively by the C^3I system to generate an accurate and unambiguous surveillance picture for the system operators.

6 CONCLUSION

The interoperability challenges are clear, but the complete solution is not. Interoperability must be

elevated to a higher level of focus, both in the joint service arena and in the international community. Many previous solutions have focused on improving data communication, neglecting the other essential components of interoperability. The common problems which continue to plague operational missions and exercises clearly highlight the lack of success which results from these limited solutions. Solving the interoperability problems will require a multi-faceted approach employing both technical and procedural modifications. Proposed technical solutions must be weighed against available funding, schedule constraints, and the potential impact on existing systems. Procedural modifications must be widely coordinated among services and allied nations.

The success of tactical aerospace C^3I operations in the coming decades will depend on the ability of mission systems to interoperate effectively. The challenge, then, is to define achievable, affordable solutions which address all aspects of interoperability, enhancing the operational effectiveness of the smaller force structures of the future.

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LA SÉCURISATION DES SYSTÈMES DE COMMANDEMENT

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INTRODUCTION

La sécurisation des systèmes d'information et de communication (ou commandement - SIC) est une nécessité afin qu'ils puissent pleinement remplir correctement les missions qui leurs sont confiées. De nombreux exemples ont montré que si cet aspect est négligé, alors les risques encourus peuvent être catastrophiques, surtout en période de crise. En effet, les données sensibles impliquées par de telles situations sont toutes stockées dans les bases de données de tels systèmes, qui sont aussi interconnectés. Par conséquent, une attaque d'une des unités d'un réseau de SIC interopérables peut être pénalisante pour l'ensemble des systèmes et peut même, au pire, paralyser le réseau globalement.

La parade contre ces attaques consiste à contrôler le plus automatiquement possible les accès aux données sensibles. Autrement dit, une surveillance des sujets et des objets de sécurité doit être effectuée conformément à un réglement rigoureux préalablement établi, appelé *politique de sécurité* du système concerné.

Cette politique de sécurité, dont l'implémentation doit être formellement prouvée pour certains niveaux d'assurance, se décline en particulier en termes de sécurité :

- informatique, concernant l'accès aux données,
- des transmissions,
- physique d'accès.

Traiter tous ces aspects, et en toute généralité, dépasse le cadre du présent exposé.

Nous nous limiterons ici à l'examen de situations typiques, souvent rencontrées, en particulier :

- l'intégration de produits du commerce,
- la réhabilitation des systèmes,
- l'interopérabilité des SIC.

La sécurité des bases de données et les processus d'identification / authentification qui sont deux points essentiels en sécurité seront également traités (nous n'examinerons pas ici les systèmes d'exploitation multiniveaux).

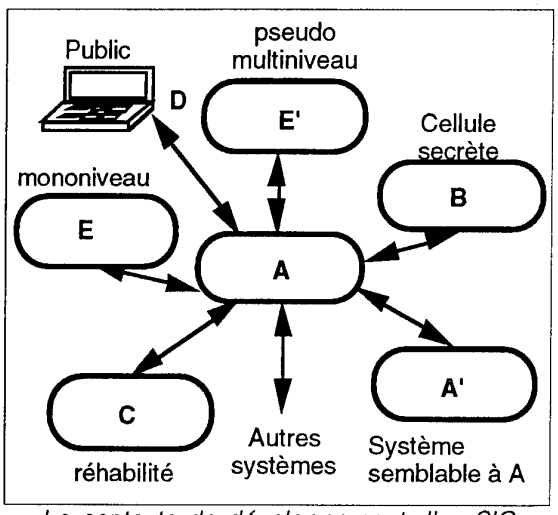
LES DIFFÉRENTES SITUATIONS QU'UN CONCEPTEUR PEUT RENCONTRER

La situation idéale pour le développeur est la conception, puis la réalisation d'un système "de toutes pièces", s'intégrant dans un contexte très homogène. Plus précisément, il s'agit d'une situation où il faut concevoir un système A qui communiquera exclusivement avec d'autres systèmes A. Malheureusement, cette situation idéale n'est pratiquement jamais réalisée. Très souvent :

- le système n'est pas nouveau (mais est une reprise d'un ancien),
- il doit être mis en communication avec d'autres systèmes parfois très différents.

Cet état de fait oblige le concepteur à composer avec l'existant, c'est-à-dire avec un ensemble de systèmes très varié, très peu homogène. Certains de ces systèmes sont anciens mais sont opérationnellement satisfaisants. D'autres ont été conçus suivant des normes ou des standards qui ont évolué. Enfin, certains appartiennent à des organisations internationales comme l'OTAN.

Le problème majeur concerne donc la coopération efficace entre tous ces systèmes, tout en respectant un certain nombre de contraintes (particulièrement lorsque la coopération doit se faire au-delà des frontières). Ces remarques d'ordre non techniques montrent que des difficultés sérieuses doivent être surmontées.



Le contexte de développement d'un SIC

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Nous avons figuré sur le schéma ci-dessus, un certain nombre de situations générales (sans prétendre être exhaustif) auxquelles le concepteur peut être techniquement confronté pour la sécurité. Il peut s'agir :

- du développement d'un SIC sécurisé nouveau (A),
- du développement d'une unité particulière d'un SIC. Par exemple, une cellule (B) hautement sécurisée. Celle-ci, en général, est incluse dans un système multiniveau (A).

Les principaux problèmes posés concernent :

- le contrôle d'accès physique à la cellule,
- le rapatriement d'informations moins confidentielles d'autres systèmes,
- l'exploitation des informations hautement confidentielles de cette cellule,
- d'un système à réhabiliter (C) (éventuellement en connexion avec A). Il s'agit là d'un logiciel qui donne fonctionnellement satisfaction, sauf en matière de sécurité. La réhabilitation est difficile, pas toujours possible. Ceci sera examiné succinctement au paragraphe **6**,
- d'un terminal public (D) déporté, à connecter à un système multiniveau A. Il faut éviter que des chevaux de Troie[1] soient introduits par cette voie publique. Il faut éviter également que des données sensibles soient extraites du système A ou détruites,
- d'une connexion de A à un système sécurisé mononiveau (E). Ce cas est assez simple à traiter,
- d'une connexion de A à un système multiniveau (E') d'ancienne génération. De tels systèmes gèrent des labels de sécurité mais n'implémentent pas toujours une politique de sécurité claire. Si l'assurance de E' est moindre que celle de A, alors le problème majeur de la connexion à établir entre E' et A est le suivant : A doit se protéger de E' afin de ne pas être pollué par ce dernier et A ne peut pas confier des données sensibles à E'. Même si certains de ces systèmes sont de confiance, les labels entre A et E' ne sont pas forcément cohérents si bien que des ajustements seront à effectuer,
- généralement de la connexion de A à d'autres systèmes. Les difficultés dépendent du niveau d'interopérabilité entre A et ces systèmes. Si ce niveau est bas, il existe des solutions simples faisant intervenir des opérateurs humains ou des passerelles de communication peu évoluées. Si le niveau est plus important, alors on se heurte au problème de la fusion des politiques de sécurité encore du domaine de la recherche (point examiné succinctement par la suite ou de la coopération entre plusieurs politiques (non examiné ici).

Tous ces points font apparaître une variété de situations où des systèmes de différentes qualités doivent être interconnectés.

Le problème majeur mis en évidence est l'interopérabilité sous ses aspects communication (avec les procédures d'identification / authentification des systèmes) et politiques de sécurité différentes.

LES PARTIES D'UN SYSTÈME CONCERNÉES PAR LA SÉCURTÉ

La figure ci-après complète la précédente puisqu'elle met en évidence les différentes parties concernées par la sécurité dans un SIC en interconnexion avec d'autres.

Comme précédemment, A est un SIC, il est doté d'une cellule B déportée gérant des données sensibles. Chaque cellule ou système est doté d'une enceinte protégée physiquement grâce à un dispositif symbolisé par  .

A ***l'intérieur de l'enceinte***, la sécurité concerne :

- le système d'exploitation qui doit être sécurisé (TOS = Trusted Operating System),
- l'accès central aux données sensibles. Ceci implique l'utilisation de bases de données (SGBD) appropriées. De telles bases existent actuellement dans le commerce au moins jusqu'au niveau B1 des TCSEC ou Orange Book (ce point sera détaillé par le suite),
- le réseau local sécurisé (LAN = Local Area Network). Il permet aux différents périphériques et machines interconnectées sur ce réseau (à l'intérieur de l'enceinte du SIC) d'effectuer des communications au niveau approprié,
- les terminaux sécurisés (écran / claviers, imprimantes, ...),

[1] Un cheval de Troie est un programme qui, en plus de réaliser les fonctions souhaitées, effectue des opérations violant la sécurité du système (par exemple, copier des données sensibles dans des fichiers publics).

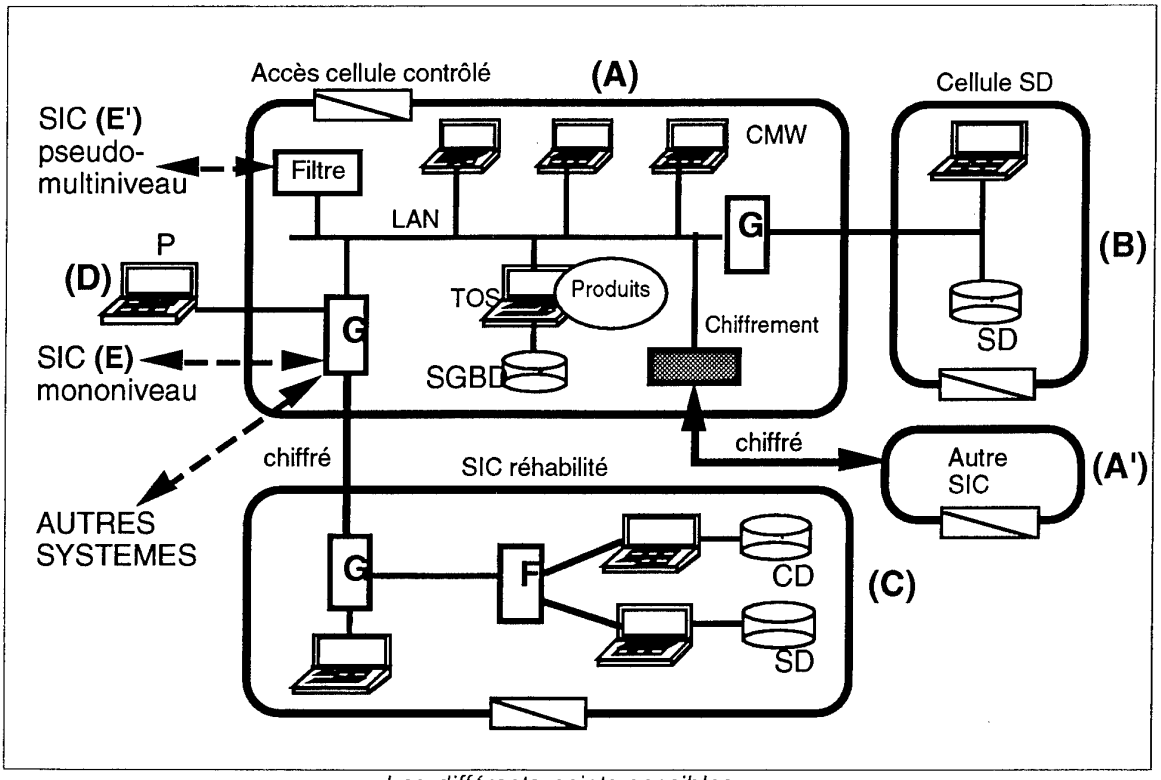
- les passerelles **G**. Elles sont nécessaires pour les communications extérieures avec d'autres systèmes multiniveau, tels que A' ou E. Ces passerelles sont des calculateurs pouvant posséder des modules de chiffrement (communication à longue distance) et d'identification / authentification,
- les filtres spéciaux Filtre. Ils sont nécessaires pour les communications avec les systèmes de qualités moindres que celles de A. Ces filtres sont implémentés sur des calculateurs contenant aussi une passerelle **G**,
- l'intégration des produits du commerce. L'utilisation de tels produits dans les SIC tend à s'imposer pour de multiples raisons. Néanmoins, d'un point de vue de la sécurité, il est assez délicat de leur confier des données sensibles,
- la cellule déportée B appartenant au SIC A contient des données très sensibles. Il doit être possible de transférer des données de A vers B, mais jamais l'inverse. Il n'existe qu'un seul niveau de confidentialité autorisé entre A et B (dans notre cas, il s'agit de Secret Défense).

En conséquence, B ne travaille qu'à un seul niveau et le SGBD utilisé n'a pas besoin d'être de même nature que celui de A. Les résultats des traitements effectués par B sont transmis à l'extérieur souvent en utilisant des supports amovibles dans lesquels l'information est chiffrée. Notons que même lorsque B travaille, il n'est pas nécessaire de déconnecter B de A.

A ***l'extérieur du SIC*** (A), d'autres systèmes peuvent lui être connectés. Il est mentionné sur la figure ci-dessus un système réhabilité C possédant deux niveaux de confidentialité.

La connexion de A à d'autres systèmes nécessite que ce dernier puisse identifier d'une façon sûre le système avec lequel il doit correspondre. Les procédures d'identification / authentification entre les systèmes sont très importantes. Elles permettent d'éviter qu'un intrus s'introduise dans le réseau.

La communication entre A et ses correspondants peut être chiffrée. Ceci permet de lutter contre les éventuelles fuites d'information mais ne suffit pas malheureusement pour garantir la disponibilité des données.



Les différents points sensibles

LES PRODUITS DU COMMERCE

On ne peut pas traiter indistinctement tous les produits du commerce. Du point de vue de la sécurité, il semble y avoir deux catégories que nous nommerons, faute de mieux, les *serveurs* et les *applicatifs*.

Les serveurs sont des produits dialoguant simultanément avec plusieurs utilisateurs (par exemple, les Systèmes d'Information Géographiques, les outils de Gestion Électronique de Documents, ...). De façon générale, ils sont composés d'un processus ayant pour rôle d'effectuer des actions pour le compte de chaque utilisateur. Ce processus doit être lancé avant tous les processus utilisateur et ne peut s'interrompre qu'une fois la dernière requête utilisateur traitée.

L'utilisation de serveurs, dont les aspects sécurité n'ont pas été pris en compte à la conception ou dont les mécanismes de sécurité n'ont pas été certifiés (selon les principes des ITSEC[1] européens ou par le NCSC[2] nord-américain), ne peuvent pas être utilisés tels quels dans un SIC sécurisé. Gérant plusieurs utilisateurs de manière complètement incontrôlable, ils peuvent sans difficulté violer les règles de confidentialité (sans parler de l'intégrité). Pour ces raisons, un SIC composé d'un tel serveur, gérant des données et des utilisateurs de niveaux de sécurité différents, ne présente aucune garantie de sécurité. Il existe toutefois des techniques pour utiliser ces serveurs, tout en offrant un plus grand contrôle sur les pièges qu'ils sont susceptibles de contenir. Ce sont les mêmes techniques que celles utilisées pour la réhabilitation de SIC : filtre et duplication (voir le paragraphe suivant). Cependant, même en les utilisant, un tel choix lors de la conception interdira un niveau d'assurance élevé sur la sécurité du SIC.

Contrairement aux serveurs, les produits que nous appelons applicatifs (compilateurs, Publication Assistée par Ordinateur, Dessin Assisté par Ordinateur, ...) sont complètement couplés aux processus utilisateurs. Il n'existe pas de processus représentant le produit et préexistant aux utilisateurs. Leur lancement est effectué par le processus utilisateur comme une commande.

Vis-à-vis du système, ils sont exécutés par le processus utilisateur et donc toutes les actions effectuées par l'applicatif sont attribuées à l'utilisateur, de même pour les processus-fils. Ainsi, même si cet applicatif contient des pièges, ces derniers ne pourront effectuer que des actions permises à l'utilisateur.

Ces produits sont plus faciles à intégrer dans un SIC sécurisé. Il faut, néanmoins, suivre une démarche précise et rigoureuse afin de s'assurer qu'un produit du commerce n'affecte pas toute la sécurité du système. Un système d'exploitation multiniveau et une gestion compartimentée des licences permettent de diminuer les risques introduits.

LA RÉHABILITATION DES SYSTÈMES

La réhabilitation de systèmes consiste à partir d'un système existant peu ou pas sécurisé pour élaborer, à moindre frais, un système assurant la même fonction mais offrant une meilleure sécurité. Deux procédés principaux permettent de réhabiliter les systèmes : l'utilisation d'un filtre, la duplication.

Un filtre est un module logiciel s'intercalant entre les processus clients et le processus serveur. Le principe est le suivant : le serveur gère toujours les mêmes données, sans se préoccuper de leur classification. Le filtre connaît l'identité des clients, ainsi que leur niveau de sécurité. Il a pour fonction de s'assurer que les clients vont uniquement recevoir en réponse à leur requête, les données qu'ils ont le droit de connaître, selon la politique de sécurité.

Il doit être mentionné qu'un type de menace est particulièrement difficile à parer dans cette approche, ce sont les pièges situés à l'intérieur du serveur. De tels pièges peuvent transformer une étiquette SD en CD, ce qui revient à déclassifier une information SD, à l'insu du filtre.

Le principe de la duplication est le suivant : on réplique le serveur en autant de copies que de niveaux de sécurité que l'on souhaite gérer. Un frontal sécurisé est intercalé entre les clients et les serveurs. Sa fonction est de transmettre aux serveurs concernés les requêtes des clients, après une éventuelle transformation. Ensuite, il doit récupérer les résultats, effectuer, si besoin, certains traitements avant de les retourner au client.

Comme la quasi totalité du code s'exécutant sur le frontal traite des étiquettes de sécurité, le frontal contient presque exclusivement du code de confiance. C'est un des inconvénients de cette solution.

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1 Les normes ITSEC (Information Technology Security Evaluation Criteria) ont été développées par 4 pays européens (Allemagne, Pays-Bas, Royaume-Uni, France). Les critères font apparaître, d'une part la notion de fonctionnalité et d'autre part celle d'assurance.

2 Le NCSC est l'organisme certificateur. Le document de base est connu sous le nom d'Orange Book.

Un autre inconvénient est l'éventualité d'un canal caché entre un client SD mal intentionné et le serveur CD. Le client peut, par l'intermédiaire des requêtes transmises au serveur CD, faire passer des informations secrètes à un cheval de Troie, qui les retournera plus tard à un client CD. Des solutions existent pour diminuer le débit d'un tel canal, mais elles impliquent une complexification de l'analyseur de requêtes et un temps de réponse accru.

L'INTEROPÉRABILITÉ

Chaque système possède une politique de sécurité qui lui est propre. Cette politique est régit par un ensemble de règles qui s'appuie sur un modèle de sécurité adopté par les concepteurs du système. Même si le modèle de Bell-Lapadula est le plus répandu, il n'est pas évident que tous les systèmes à mettre en communication aient une politique de sécurité s'appuyant complètement sur ce modèle.

Certaines opérations pourraient être permises par un système et interdites par l'autre. Plusieurs solutions peuvent être envisagées pour résoudre ce problème. L'application de celles-ci dépend du *niveau d'interopérabilité* auquel peuvent prétendre les systèmes qui doivent coopérer.

L'OTAN distingue actuellement 6 niveaux, qui prennent en compte l'aptitude des systèmes à "se comprendre", plus ou moins automatiquement (le niveau **6** correspond à l'interopérabilité complète). Globalement, les niveaux **1** à **3** correspondent à une communication réalisée ***sans*** connexion physique entre les systèmes. L'échange est initialisé par des opérateurs ayant des droits d'accès chacun sur leur propre système. Les niveaux **4** à **6** utilisent, par contre, une connexion physique entre les systèmes et exigent que les utilisateurs ayant lancé la communication aient des droits d'accès sur un certain domaine de l'autre système (mode croisé).

Interopérabilité de niveau 1 à 3

L'idée principale de ce type d'interopérabilité est que la traduction des données et le passage entre les différentes politiques de sécurité s'effectue manuellement par un opérateur humain (opérateur de transfert). Ainsi, le schéma est à peu près le suivant : un opérateur extrait les données d'un système en se soumettant à la politique de ce dernier. Puis, il les rentre dans l'autre système après avoir effectué les opérations nécessaires de traduction concernant l'interprétation des données. Cette solution est intéressante, en dépit de la lenteur de la communication, car les éventuels conflits sont toujours réglés sans aucune ambiguïté. Néanmoins, dans le cas où les opérateurs de transfert doivent posséder des droits d'accès sur chacun des deux systèmes, certaines situations peuvent limiter la coopération. Par exemple, si l'opérateur de transfert possède des droits sur la catégorie "nucléaire" pour l'un des systèmes, mais pas pour l'autre, alors l'échange n'est pas possible, ce qui peut être parfois très pénalisant si cet échange est nécessaire.

Ce type d'interopérabilité, s'il règle les problèmes de sécurité, est néanmoins trop lourd. En effet, la communication de données volumineuses est quasi impossible.

Interopérabilité de niveau 4 à 6

La présence d'une connexion entre les 2 systèmes ne permet pas d'effectuer une "juxtaposition" des politiques réalisée par une traduction effectuée par des opérateurs humains comme dans le cas précédent.

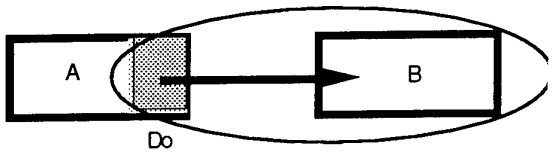
Comme précédemment, la limitation du domaine à échanger, si elle est possible automatiquement, est la solution la plus simple techniquement. Par exemple, on pourrait imaginer que seules des données non classifiées d'une certaine catégorie sont exportables. Néanmoins, une telle solution est vue comme très réductrice, car en général les opérationnels veulent aller plus loin. Pour pouvoir réaliser une connexion plus intéressante, il faut que les 2 systèmes puissent s'entendre sur les niveaux des données à communiquer, et sur les catégories concernées.

Deux modes principaux d'échange peuvent être envisagés :

- le mode direct,
- le mode consenti.

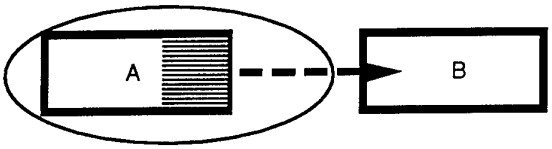
Lorsqu'un système permet le ***mode direct***, cela signifie qu'il dispose d'un domaine particulier *Do* de données interopérables. Autrement dit, l'ensemble des informations qu'il détient n'est pas exportable, hormis celles qui sont contenues dans ce domaine interopérable. Tout système extérieur B peut y accéder à condition qu'il soit possible d'établir un niveau d'échange adéquat entre A et B pour *Do*. Si tel est le cas, B a accès a tout *Do* en fonction de *sa propre politique de sécurité*.

Ainsi, il existe donc un domaine d'échange bien spécifié (*Do*) d'un niveau donné, auquel tous les systèmes ont accès (en lecture seule). Ce mode est souvent utilisé pour permettre l'accès à une *situation tactique* entretenue par un système dédié.



Mode direct, échange réglé selon la politique de B

Lorsque les 2 systèmes A et B sont interopérables au travers d'un mode de sécurité ***consenti,*** par exemple dans le sens *A → B,* alors B ne peut pas intervenir directement sur A. Il y a transmission par B d'une demande qui est ensuite exécutée par A s'il consent à y répondre. En fait, A répondra en fonction de sa propre politique de sécurité. L'interopérabilité est donc, vis-à-vis de la sécurité, un couplage plus faible que précédemment. Le système B est vu par A comme un *sujet,* qui peut a priori faire toutes les opérations pour lesquelles il a les droits sur A. Toutefois, A garde un droit de veto pour interdire dynamiquement certains échanges (ce cas correspond au niveau **6** d'interopérabilité OTAN).



Mode consenti, échange réglé suivant la politique de A

LES BASES DE DONNÉES SÉCURISÉES

Les bases de données sont des composants essentiels des SIC. Leur fonction première est de gérer des grands volumes de données persistantes, mais ce n'est pas la seule. Un SGBD permet aussi le partage des données entre plusieurs utilisateurs, une modélisation permettant un accès facile et puissant grâce à un langage de requêtes.

Dans le domaine des SGBD (Système de Gestion de Base de Données) sécurisées, seule l'approche relationnelle offre aujourd'hui des solutions commerciales.

Cette avance s'explique facilement puisque les SGBDR (SGBD Relationnelles) sont antérieurs aux SGBDO (SGBD Objet) d'une dizaine d'années environ.

Rappel de l'existant :

Parmi les produits sécurisés, il faut distinguer deux grandes classes :

- les SGBD n'assurant que le besoin d'en connaître, au moyen de contrôles d'accès discrétionnaires (*DAC : Discretionary Access Control*). Les fonctions disponibles sont fondées sur l'hypothèse que chaque donnée possède un propriétaire qui décide des droits des autres utilisateurs sur ses données,
- les SGBD gérant en plus le droit d'en connaître, par des contrôles d'accès obligatoires (*MAC : Mandatory Access Control*), aussi connus sous le nom de multiniveau. Chaque utilisateur et chaque donnée possèdent un niveau de sécurité.

La première catégorie correspond aux niveaux C1 et C2 de l'Orange Book, et la seconde aux niveaux supérieurs (B1, B2, B3, A1).

Les éditeurs de SGBDR proposent deux types de produits : une version standard, au mieux évaluée au niveau C2, et une version sécurisée multiniveau, au mieux au niveau B1.

Les principales fonctionnalités demandées par le niveau C2 sont la réutilisation d'objets (*object reuse*), exigeant que tout conteneur d'information soit remis à zéro avant toute réutilisation, et l'audit des actions concernant la sécurité (identification, authentification, accès et destruction d'objets).

Tous les SGBD multiniveau demandent un système d'exploitation multiniveau.

Les attentes

Les SIC ont mis en évidence des besoins de bases de données multimédia et réparties. En effet, les informations à gérer sont diverses, complexes et très nombreuses. On peut citer par exemple : les données de représentation de la situation (incluant souvent une cartographie vectorielle), les données du renseignement (photos, plans, fiches ...), les documents, les descriptions d'objectifs (objets complexes), les données météo, etc..

Une si grande variété de données ne peut pas être facilement gérée par des bases de données relationnelles. Par contre, grâce à leur possibilité de typage riche, les SGBDO autorisent une modélisation aisée de ces données.

De nombreux SGBDO sont présents sur le marché. Malheureusement, les fonctions de sécurité de ces produits sont actuellement largement insuffisantes pour couvrir les besoins des SIC. Dans le meilleur des cas, seuls des contrôles discrétionnaires peuvent être mis en place.

Cette lacune n'est pas due uniquement à la jeunesse des produits. Plaquer des contrôles d'accès discrétionnaires ou obligatoires sur le modèle des objets présente des difficultés techniques réelles.

Les SGBDO offrant de réelles possibilités pour développer les SIC actuels et futurs, leur sécurisation devient donc un réel besoin, il est donc pénalisant de les laisser de côté pour leur faiblesse en sécurité. Les qualités attendues de telles bases sécurisées sont l'ouverture à tous les langages (C, C++, O2C ou OQL), la compatibilité avec les applications existantes et une faible dégradation des performances.

Les difficultés

Les points que nous allons rapidement décrire présentent des difficultés en cours d'étude, pouvant déboucher sur des solutions industrielles à moyen terme.

- Langages de requêtes.
- Les langages de requêtes couramment employés dans les SGBD sont SQL pour les SGBDR et OQL pour le SGBDO. Aucun des deux n'est prévu pour interroger une base multiniveau. Par exemple, la requête "rechercher tous les employés dont la classification est inférieure à celle de leur salaire" est soit impossible à exprimer, soit une solution dépendant du produit utilisé.
- Gestion des transactions.
- Les SGBD utilisent les transactions pour régler les problèmes de contrôles de concurrence et de tolérance aux pannes (reprise). Les protocoles les plus utilisés dans ce domaine sont le verrouillage à deux phases pour le contrôle de concurrence et la gestion d'un journal de pages pour la reprise. Il se trouve que le verrouillage introduit des canaux cachés (le plus souvent temporels) entre transactions de différents niveaux. De la même façon, le rejet volontaire d'une transaction par un utilisateur peut affecter les transactions de plus haut niveau.
- Leurres
  Pour cacher l'existence d'une information à un utilisateur, une solution est d'introduire des leurres dans la base au moyen de la poly-instantiation : pour chaque niveau inférieur à la version "vraie", existe une version ayant une valeur fictive, pouvant être différente pour chaque niveau.

  Ces leurres sont le meilleur moyen pour dissimuler l'existence d'une information sensible. Ils introduisent cependant un certain nombre de difficultés (comment déterminer les vraies valeurs, comment interroger les leurres ?).

  Les produits actuels ne permettent pas la mise en place de leurre.
- Agrégation

  Le problème d'agrégation apparaît chaque fois que la sensibilité d'un agrégat de données est strictement supérieure à celle de chacun de ses composants. Ce type d'agrégat nécessite un traitement différent des agrégats "normaux", dont la sensibilité est égale au maximum de la sensibilité de ses composants. Ce thème demeure encore un sujet de recherche.

CONCLUSION

La sécurisation des SIC nécessite plusieurs techniques de nature différente : chiffrement, multiniveau, matériel, ... Ces techniques interviennent dans les SIC depuis la protection du périmètre de sécurité (rôle du matériel) jusqu'au cœur du système stockant les données sensibles (où des techniques informatiques prennent le relai), sans oublier la communication entre les systèmes. Pour réaliser cette sécurisation, les industriels doivent avoir une approche globale intégrant tous ces aspects. Ceci nécessite non seulement l'application d'une méthodologie rigoureuse, mais également un savoir faire à spectre large.

La sécurité des systèmes est une préoccupation de SAGEM depuis plusieurs années. Elle comprend non seulement une activité centrée sur le chiffrement de l'information (pour la confidentialité des données et l'identification/authentification des systèmes et des personnes par clés secrètes et publiques), mais également :

- la réalisation de systèmes de reconnaissance d'empreintes digitales,
- les études et développements concernant la technique multiniveau.

La maîtrise de l'ensemble de ces techniques permet à SAGEM la réalisation de la sécurité des systèmes complexes que sont les SIC.

An Integrated Theater Battle Management C2 Architecture Based on Commercially Available Software

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SUMMARY

For the past two decades, "stove-pipe" Command and Control (C2) information systems have proliferated within the Department of Defense (DOD). This proliferation has resulted in duplication of development effort, systems which are not interoperable, and large life-cycle costs. To a large extent, these systems have been built with uniquely developed software. Much of this unique software constitutes what is commonly referred to as the software infrastructure (e.g., system level services and support services for mission application software). For Theater Battle Management (TBM) C2 information systems, the software infrastructures are inherently the same with regard to the functions and services they provide. Technically, these systems could benefit from a common software infrastructure.

With advances in the commercial software market, the realization of such a common infrastructure no longer needs to rely on uniquely-developed software. The commercial marketplace provides solutions for significant portions of the software infrastructure based on open systems standards and mature standards-based products.

1.0 INTRODUCTION

DOD Migration of C2 Automated Information Systems (AISs)

The selection of DOD migration systems is an initial step in a process that will effectively change the methods by which DOD acquires and fields AISs. At present, DOD Program Managers each build an entire AIS to satisfy an assigned set of operational requirements. Each AIS, by definition, consists of "computer hardware, computer software, telecommunications, information technology, personnel, and other resources which collect, record, process, store, communicate, retrieve, and display information."

The current method of systems acquisition has resulted in duplication of functionality, especially in those components that could be considered "infrastructure." It has also exacerbated the difficulties inherent in achieving interoperability among DOD AISs. The goal of DOD systems migration is to reduce costs, alleviate duplication of functionality, and reduce interoperability limitations by moving DOD AISs into a distributed, client-server computing environment with a single underlying infrastructure. In this regard, mission- and function-specific applications would be supported by a Common Operating Environment (COE) (e.g., system services, support applications, common-user tools), a consistent data model, standardized data elements, and consistent applications development conventions (e.g., Application Programming Interfaces (APIs), directory structures, naming conventions). Application development will be governed by consistent standards (i.e., DOD Technical Architecture Framework for Information Management (TAFIM)) and certain key principles of standards-based versus non-technical architecture industry accepted proprietary-based solutions, Commercial Off-the-Shelf (COTS) versus Government Off-the-Shelf (GOTS), and user-tailored versus standardized hardware/software configurations.

Today, efforts are ongoing among the U.S. military services to establish a single, global Command, Control, Communications, and Intelligence (C3I) system to support the warfighter. This single C3I system will utilize a COE composed of a set of integrated support services that support C3I mission application software requirements and a software development environment which assists in the development of mission application software by capitalizing on software infrastructure support services. In the near-term, the COE includes support applications, platform services, and reusable software components. The mid-term COE is a target profile of standards and other services in the following areas: Programming, User Interface, Data Management, and Operating System. The COE is to migrate to eventual compliance with the DOD TAFIM profile. Non-Developmental Items (NDIs), including COTS and GOTS, as required, are the preferred COE implementation approach.

DOD and commercial applications are different but also similar in many ways. Distinguishing differences often lie in the time critical requirements to process information as witnessed in processing requirements for real-time embedded applications versus non-real time AISs. Additionally, within the areas of C3I

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Systems versus Commercial AISs, we often find distinguishing characteristics in the areas of fault-tolerance and high-availability.

However, as the commercial/business world becomes more dependent upon their automated information systems to accommodate soft real-time transaction processing (e.g., various stock market and financial trade market systems), as well as to address the requirements of highly available fault-tolerant systems, the demands on the commercial software market are increasing to produce components to address these requirements.

We contend that much of the functionality between these commercial systems and DOD AISs are the same. Furthermore, the commercial software market has matured to make available numerous components that will satisfy the requirements of DOD AISs in a cost effective manner. This paper identifies work ongoing within the government, some conducted by The MITRE Corporation, that indicates the potential use of commercial technology within TBM C2 AISs. This work spans a spectrum from: studies conducted to determine the feasibility and cost of AIS migration to a single software infrastructure and prototyping efforts to replace uniquely developed functionality with commercial software. Included in this spectrum is work on encapsulating legacy components to allow reuse with minimal re-engineering.

2.0 EFFORTS TO DEFINE A COMMON FUNCTIONAL ARCHITECTURE

As part of the U.S. Air Force consolidation of AIS systems, a TBM C2 integration study was conducted by the Air Force Materiel Command's Electronic Systems Center with support from The MITRE Corporation. This study investigated the consolidation of four Air Force systems - Contingency Theater Automated Planning System (CTAPS), Wing Command and Control System (WCCS), Air Mobility Command (AMC) C2 Information Processing System (IPS) (theater level and wing level) and Command Theater Information System (CTIS) Digital Decision Display System (3DS) - into a standard force/unit level system. The Air Force world-wide force and unit level user community participated in this study through several users meetings.

The motivation to consolidate efforts comes from several needs. Operationally, these systems need to manage similar information and present the information to the same or similar users. Technically, these systems have substantially similar infrastructure requirements and could benefit from a common approach. That is, a similar technical approach would yield improved operational effectiveness, as well as logistics and life cycle cost savings. Such savings would be in the areas of training, documentation, and software maintenance. Also, fewer systems to deploy during crisis and wartime operations would lessen airlift and hardware space requirements.

One of the critical findings of this study was the need to establish a common technical infrastructure for both force and wing level systems. This software infrastructure would provide a standard set of services to the force and wing level applications. The infrastructure would provide the warfighter with a basis to build a system with improved survivability, information consistency and integrity, and provide a basis for building a multilevel secure system. It would support building mission applications with a standard User System Interface (USI) to provide the warfighter with a consistent look and feel across force and wing level applications (to include standard map backgrounds and map symbology). Additionally, a common software infrastructure would allow for a uniform set of database management services to facilitate the information re-engineering that must be performed across the heterogeneous databases. This would facilitate the implementation of standardized data elements.

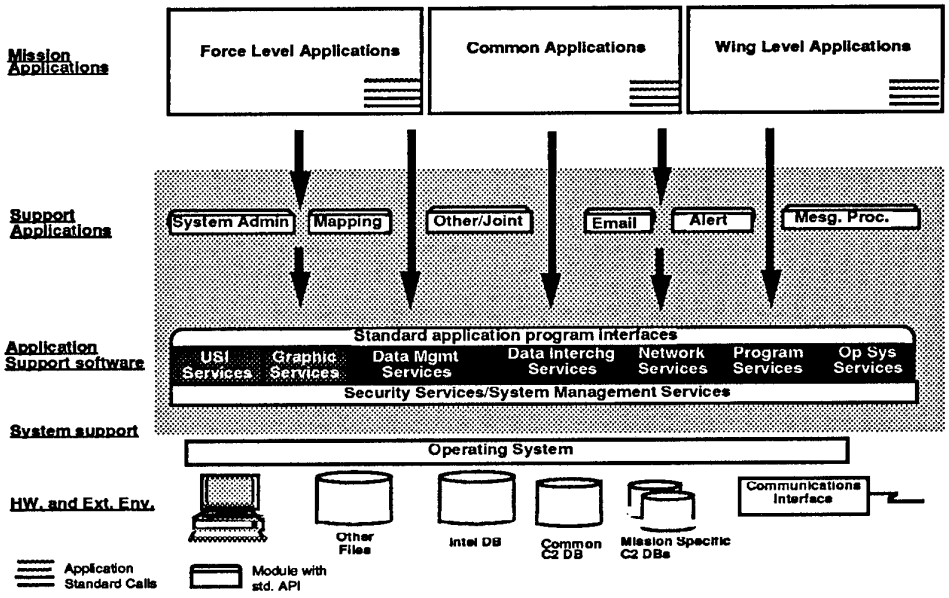


Figure 1. TBM C2 Target Software Architecture

Figure 1 presents a target software architecture that will support all TBM C2 systems, whether they are force (i.e., theater) level applications, wing level applications, or mission oriented applications that are used at both levels. Mission applications include the functional software unique to a specific command. Examples of mission level applications include software for intelligence, air campaign planning and execution/monitoring, scheduling, maintenance, logistics, and weather.

The most significant feature of this architecture is the use of a common underlying software infrastructure. This software infrastructure is highlighted in the shaded area of Figure 1. It serves to interface mission applications to the underlying system support components of the operating system and associated hardware (e.g., disks, displays, and communications interfaces).

Support applications are utilities or services that provide commonly needed functionality to support C2, and that are not specific to a particular mission application. These include software such as electronic mail, message alert, common mapping, system administration tools, video manipulation, imagery handling service, and message handling software. Some support applications can be used directly by the user (e.g., E-mail). They can also be used to implement a mission specific application. In this case, a standard API is provided for each support application in order to interface it with the mission applications.

The lowest level of the infrastructure software is the application support software. This software is comprised primarily of COTS products configured according to TBM C2 standards and implementation specifications to provide several lower-level services. USI services include the MOTIF/X Windows software. Graphics services include configured COTS software to support both two dimension and three dimension graphics. Data management services include a common set of database management system software, database replication services, and database backup/recovery services. It may also contain database access modules and APIs to mission applications which provide standard routines for accessing and updating relational databases, track databases, map databases, and other data files. The Data Interchange Services and Networking Services provide complementary functions to support message, file, and remote terminal protocols. They also include distributed computing services, and network management services.

System support refers to underlying operating system software, file management, and other software interfaces to computer hardware peripherals and external communications.

The infrastructure will provide the warfighter with improvements in information consistency and integrity and system survivability. Information consistency and integrity means that all users will view the same value of operational items (e.g., number of aircraft possessed) and that the system will ensure the integrity of this information.

Improvements in survivability means that in the event a critical part of the system is unavailable, due to equipment failure or enemy action, the system will continue to have access to stored information through redundancy. Additionally, interoperability between the force and unit levels will be enhanced by using a common infrastructure. Information, including the

Air Tasking Order (ATO), could be transmitted through database-to-database transfers instead of the present methods of formatted messages. Such formatted messages would still be needed for other users. However, significant time savings and communications bandwidth savings would accrue.

A common technical infrastructure will mean less software to maintain. Instead of maintaining separate software support systems, fewer lines of code would be fielded and significant life cycle savings would result. Significantly less software to maintain translates into sizable life cycle cost savings.

3.0 IMPLICATIONS OF USING COMMERCIAL TECHNOLOGY

Several criteria should be investigated when considering the use of commercial technology. Is the time ripe to migrate from unique development to commercial technology? Can all of the system requirements/conditions be met? What is the state of commercial technology, is it migrating consistent with standards, and is it a viable product in the marketplace?

Additionally, some analysis should be performed to provide the basis for sound engineering judgment: technical versus performance trade offs, cost/benefit economic analysis, and the review of requirements. All of these are explored in greater detail.

State of Commercial Technology

In addition to understanding the requirements of the software architecture, the state of commercial software must be well researched, and well understood, before any determination can be made regarding its use for military or commercial infrastructures. As an example, in 1987 when the Air Operations Center (AOC) portion of CTAPS was being designed and implemented, several important technologies were not commercially available. While commercial relational databases and graphical windowing systems were available, commercial solutions for distributed computing systems and distributed file systems were not. This lack of commercial software caused the government to pay for custom development to implement validated user requirements. Now, eight years later, commercial solutions to these requirements are finding their way to the market place; and into DOD C2 AISs.

The initial uses of commercial technology in DOD C2 systems have been in the traditional areas: operating systems and typical business applications (e.g., spreadsheets, relational databases, and word processing). These are market areas that found a significant customer base and reached maturity quickly. With the growth of AISs in the commercial sector, and in particular AISs to support larger multi-location corporations, other functional areas such as network and system management have found commercial solutions. A review of the infrastructure functional areas produced the following results:

Table 1. Current State of Commercially Available Technology

Infrastructure area	Commercially available	Meets TBM C2 Rqmnts.	Mature technology	Multiple vendors
System Admin.	Yes	Yes (1)	No	Yes
Mapping	Yes	No	No	Yes
Email	Yes	Yes (1)	Yes	Yes
Alert Services	Yes	Yes	Yes	Yes
Message Processing	No	No	Yes	Yes
USI Services	Yes	Yes (1)	Yes	Yes
Graphic Services	Yes	Yes	Yes	Yes
Data Management Services	Some	Yes (1)	Yes (3)	Yes
Data Interchange Services	No	No (2)	No	?
Network Services	Yes	Yes	Yes	Yes
Program Services	Some	Yes	Yes	Yes
OS Services	Yes	Yes	Yes	Yes

Note 1: With some customization of commercial product using vendor supplied tools.
Note 2: Unique DOD data formats discourages much commercial development.
Note 3: Data replication still appears to be a young technology.

Table 2. State of Future Commercially Available Technology

Infrastructure area	Commercially available	Meets TBM C2 Rqmnts.	Mature technology	Multiple vendors
System Admin.	Yes	Yes (1)	Yes	Yes
Mapping	Yes	No	No	Yes
Email	Yes	Yes	Yes	Yes
Alert Services	Yes	Yes	Yes	Yes
Message Processing	No	No	Yes	Yes
USI Services	Yes	Yes (1)	Yes	Yes
Graphic Services	Yes	Yes	Yes	Yes
Data Management Services	Some	Yes	Yes	Yes
Data Interchange Services	No	No	No	Yes
Network Services	Yes	Yes	Yes	Yes
Program Services	Some	Yes	Yes	Yes
OS Services	Yes	Yes	Yes	Yes

The COTS picture changes very rapidly and should be continuously evaluated. Many requirements that could not be solved by commercial solutions as little as a year ago now have viable commercial solutions. In some cases, the solution did not exist at all; in other cases, the solution existed but could not be used because of inadequate performance, lack of sufficient functionality, or an inability to meet perceived user environmental requirements. With a greater emphasis on commercial use of software within the government, more and more infrastructure areas are capable of being solved by commercial solutions. Moreover, many new technologies like the Open Software Foundation's Distributed Computing Environment (DCE) and the Object Management Group's (OMG) Common Object Request Broker Architecture (CORBA) provide solutions that transcend the boundaries between infrastructure areas. For example, DCE could provide solutions to security and system administration as well as support for distributed computing.

Technologies like the CORBA, and specifications like the Common Open Software Environment (COSE), and the operating system interface SPEC 1170 provide even greater functionality and open standards and mitigate some of the risks of mixing commercial technology with unique development. Our investigations indicate that additional capabilities will be served by commercial solutions in the near future.

4.0 MIGRATION FROM LEGACY SYSTEMS

Several items ease the migration of legacy systems. First and foremost is an abstract definition of the framework (i.e., software architecture) for the desired infrastructure. An abstract design allows the government to have a sense of the desired solution unconstrained by the current state of the technology. With this objective design, an understanding of the current and future trends in software technology, and an understanding of the functional requirements of the current system, the government can begin to analyze the available solutions and map out the steps needed to migrate the legacy system. Depending on the size of the system (i.e., the number of components to migrate), a migration model can be constructed.

The government must also have a good understanding of the state of development of the legacy system. This implies an understanding of the maturity of the software, its current ability to meet the user's requirements, how well it was developed (e.g., complexity, clarity, defined interfaces, modularity), and how easy it is to maintain. Migration from existing interfaces and services will cause new development in the migrated legacy components. Although not exhaustive, the following steps construct the minimum migration model:

How - The Method
This step is where the government makes an evaluation of the methods that might be used to migrate from unique development to commercial solutions. This step takes into account all of the information gained in the survey of the commercial marketplace, what products are becoming mature, and what new products are showing up.

Once the preparatory work is done, the government must determine a systematic way to bring commercial products into C2 information systems. This implies a standardized methodology that might be empirically defined, or might have been used on a previous project.

The methodology must also be able to accommodate partial or total replacement of existing components, depending on:

- the modularity of the components in the legacy system
- the maturity of the components in the legacy system
- the availability of capable commercial replacements.

The most difficult part in the migration is controlling the potential ripple effect of replacing software components in an established system. The use of software reverse engineering tools to identify potential conflict areas will help to lessen, but may not prevent, new problems based on software component replacement.

When - The Timing
Determining when to migrate, or replace, unique legacy components is the most difficult of all the migration steps. This is true partially because there is no good source of historical data, and partially because there are no good metrics for determining the migration timing. It depends on many criteria, some that the program manager has little control over like issues of commercial availability, but also others that can be understood and characterized with the use of tradeoff analysis and studies.

5.0 MIGRATION TRADEOFFS

Technical/Performance Tradeoffs
Of all of the tradeoffs to be considered during migration planning, technical/performance is one of the most difficult. Although these are the tradeoffs that system/software engineers are most comfortable with, issues of architectural complexity (e.g., client/server design, application and data distribution, distributed computing) make these tradeoffs difficult. Additional difficulty in this set of tradeoffs comes from not having a clear understanding of the functional requirements or the capabilities of the vendor's products, or the ability of the vendors products to be modified or tailored to meet requirements.

If the software architecture has stringent performance requirements, as is often typical of large AISs, whether military or commercial, a simulation of the architecture may be warranted. This simulation can provide insight into the performance of the software architecture. This simulation may be difficult to assemble and run since the actual performance values of many of the pieces of commercial software may be unknown. In this case, a series of prototypes, ranging from notional to full capability may provide the data needed to validate the use of commercial standards based components in the software architecture.

Requirements Review
It is important to note that the ability to replace unique development with commercially available technology is not a panacea, nor is it a replacement for a good understanding of the functional requirements of the system. The increased availability of commercial technology should eventually force a definition of the requirements in a broader, less rigid fashion. Rigidly defining the requirements (leaving little room for negotiation) almost always causes unique development.

There will be cases where a closer examination (cost/benefits tradeoff) of the requirements may indicate that the vendor's commercial solution is not capable of meeting the user's needs. However, in this case, development using vendor provided tools, may provide an adequate solution to the requirement as opposed to new custom development. The availability of commercial technology should be used as a metric to justify examination of requirements, but it should never be used to cause the capitulation of valid requirements. The cost of implementing a requirement through unique development is investigated through an economic analysis.

Economic Tradeoffs
While replacing custom developed components has the potential to reduce future maintenance costs, and decrease overall system complexity, it often requires investment from this years' budget to gain perceived advantages in the future. There is a perception that significantly higher costs are associated with the use of COTS. An economic analysis performed for a DOD C2 AIS indicated that replacement of a custom developed system-support service component with COTS, including licensing, was no more expensive than the custom-developed application, even without consideration to long-term maintenance. This analysis provides an example of how the government can leverage off of the product and domain expertise of a commercial vendor instead of bearing the burden of development and maintenance of custom applications.

Leveraging off of the vendor's expertise does not come without its own set of associated risks. By accepting commercial technology, the government gives up the right to source code, and potentially to data rights. Using commercial technology often results in a right to use license rather than complete and unchallenged ownership. As long as the commercial software meets the stated requirements, or can be extended using vendor provided tools, the lack of source code, or the right to use license should not cause problems.

Other issues arise with respect to the difficulties of contracting for the use of commercial technology. Even if the contract can be established with sufficient flexibility on the part of the government, there is always a difficulty in the timing between contract award dates and COTS availability dates. Additionally, the government always has the ability to

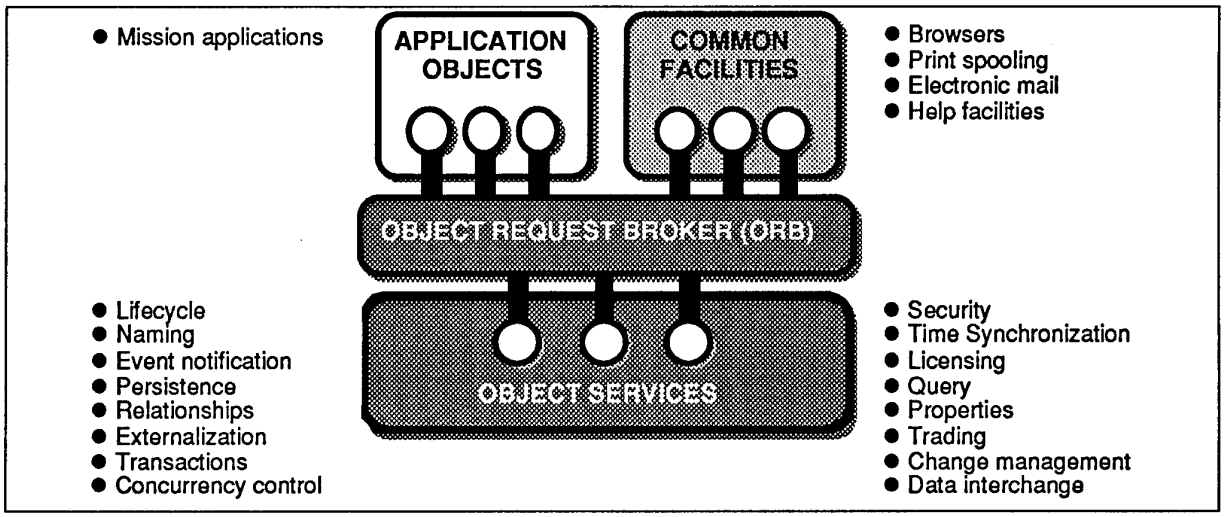


Figure 2. Object Management Architecture (OMA)

direct the contractor to use COTS instead of custom development, but this is always done with an acceptance of risk on the part of the government.

Another compounding factor regarding the use of commercial technology is the pace and volatility of the commercial marketplace. When considering a commercial product, the size of the corporation may not be as important a consideration as several other criteria. For example, if the corporation is a member of a consortium that specifies standards and practices, the corporation's products may stand a higher chance of being widely accepted as a defacto industry standard. Additionally, the consortiums also help to focus "product development" as a solution to vertical markets.

6.0 EVOLVING FROM LEGACY WITH COMMERCIAL TECHNOLOGY

The integration of existing C2 systems presents many technical challenges. The existing systems were generally developed to automate individual manual processes with little concern for future integration. As a result, the integration effort must address the inconsistent subsystem interfaces, inconsistent use of system services, inconsistent user interfaces, and duplicative databases. Current approaches have shortfalls. The use of commercial technology in military and government systems is recognized as a primary means to reduce cost and time to deployment. The commercial world is developing tools based on open systems and object-oriented technology through cooperative organizations such as the Open Software Foundation (OSF) and OMG.

Distributed Object Management (DOM) is a key underlying technology for enabling distributed processing in distributed heterogeneous information systems. A DOM system provides a means by which software components may be instantiated, accessed, coordinated, and otherwise controlled, independent of the underlying platforms. DOM systems make it possible to develop complex systems that are made up of legacy applications and new applications developed by different organizations, because the application interfaces are well defined and catalogued for easy access and browsing. In addition, DOM systems provide a uniform set of services (change management, naming, transactions, security, query, backup, replication, etc.) that can be used by any application.

OMG

The OMG is a consortium of over 400 companies, including vendors such as Sun, Hewlett-Packard, IBM, Microsoft, Apple, Digital Equipment Corporation (DEC) and database management system developers such as Oracle, Sybase, and Object Design. The members of OMG [OMAG 92] have "a shared goal of developing and using integrated software systems." The mission of OMG is to develop "a set of standard interfaces for interoperable software components." OMG is developing a standard for object-oriented middleware that realizes interoperability among independently developed applications across networks of heterogeneous computers by defining the Object Management Architecture (OMA), an architectural framework with supporting detailed interface specifications (Figure 2).

Department of Defense Intelligence Information Systems (DODIIS) and DOD TAFIM Profiles

In our opinion, the CORBA, Common Object Support Software (COSS), and Common Object File System (COFS) specifications appear to supplement the DODIIS Client-Server Environment (CSE) [Sure94] and the DOD TAFIM profiles. The CSE and TAFIM profiles specify a collection of guidelines, data formats, APIs, protocols, and COTS application programs. CORBA might be considered to replace the networking components of these profiles.

Table 3a. DOM Products

	DEC			HP	Sun	
	OpenVMS	OSF/1	Ultrix	HP-UX	Solaris	SunOS
IBM SOM/DSOM	—	—	—	95	—	—
HyperDesk (withdrawn)	—	—	—	93	—	93
Digital ACAS (replaced)	93	93	93	93	—	93
Digital ObjectBroker	94	94	94	94	—	94
HP Distributed SmallTalk	—	—	—	now	now	now
HP ORB Plus	—	—	—	95	—	—
IONA Orbix	—	94	now	now	now	now
Sun DOE + OpenStep	—	—	—	—	95	—

Table 3b. DOM Products

	IBM				Apple	Microsoft	
	AIX	MVS	OS/400	OS/2	MacOS	NT	Windows
IBM SOM/DSOM	now	94	95	now	—	now	now
HyperDesk (withdrawn)	93	—	—	—	—	—	93
Digital ACAS (replaced)	93	—	—	—	93	93	93
Digital ObjectBroker	94	—	—	—	94	94	94
HP Distributed SmallTalk	now	—	—	now	now	now	now
HP ORB Plus	—	—	—	—	—	—	—
IONA Orbix	94	—	—	94	—	now	94
Sun DOE + OpenStep	—	—	—	—	—	—	—

Standard user interface objects can be developed using CORBA that would help enforce a style guide "look and feel" to applications. CORBA wrappers provide interoperability among application service components in a uniform manner. The DODIIS CSE intends to follow the CORBA, COSS, and COFS specifications as they continue to evolve with a view toward inclusion of these specifications in future releases of its profiles.

Other DOM Products

Tables 3a and 3b show the major vendors' rollout plans for object technology. The vendors themselves were the source of all of the information supplied in the table. Some of the information was taken from *Open Systems Today*, August 1, 1994, page 69. The "—" in the tables indicates that the implementation is not planned at the present time; "94" means it is planned for late 1994/early 1995.

In addition to the these products, Taligent and Apple plan to use IBM's DSOM. Microsoft and Digital are developing a Common Object Model (COM) specification that is similar to CORBA in many ways. DEC plans to provide a gateway between ObjectBroker objects and COM objects.

The Use of CORBA Products, A 1995 Perspective

DOM technology's greatest strength is that it can provide interoperability among mission applications, support applications, and distributed services. It can be used to wrap data formats, APIs, application programs, and enforce guidelines and protocols. Old stovepipe applications can be encapsulated with relatively little effort so that they can continue to be used in the evolving system until they can be modernized or replaced.

DOM technology provides a means to support the development of evolvable systems. An evolvable system changes over time to exploit more powerful hardware and to address new user requirements which necessitate: the incorporation of new applications (mission or COTS), the incorporation of new databases (information sources), or the modification of existing applications and/or database organization (structure or schema). An evolvable system is generally complex involving heterogeneous hardware (both different vendors and different generations) and heterogeneous user communities (users using the same applications/ databases may have different tasks to perform and/or different levels of training).

We believe DOM technology holds great promise, however, it must be said that from an early 1995 perspective, it is still too immature to be used in mission critical systems. OMG specifications (CORBA/COSS/COFS) are immature. The CORBA 1.2 specification did not enforce interoperability

among DOM vendors; however, in early 1995, agreement for the CORBA 2.0 has been reached that specifies how DOMS should interoperate. However, there have been a number of early agreements among UNIX vendors to develop DOM environments that are capable of interoperating. (For example, Candle, HP, and IBM demonstrated interoperable products at Object World San Francisco in July 1994, as did Fujitsu, IONA, Post Modern Computing, and SunSoft, and Digital demonstrated access to their products from Microsoft Windows applications via OLE 2.0.)

By late 1995, we can expect that there will be many CORBA-compliant commercial products available. Many object services specifications should be agreed on and several should be available in DOM products. There should be some off-the-shelf applications and many encapsulated legacy applications available. There may be some support for soft real-time processing to support multimedia. By 1995, the government should have an acquisition strategy in place for information systems. Hardware platforms that are capable of running CORBA-compliant DOMs should be required. Application developers should be required to develop CORBA-compliant Interface Definition Language (IDL) interfaces to their applications. Further, application developers should be required to anticipate the availability of object services and facilities--either to make use of interfaces for already specified object services/ facilities or to encapsulate the services/facilities they develop so that they can be replaced easily when appropriate object services/facilities are available.

By 1997, CORBA vendor products should be interoperable. Many object services should be specified and available. Many off-the-shelf applications should exist. DOM vendors should be able to support some real-time processing, at least as far as supporting multimedia applications. Although this level of support may not be adequate for supporting the hard real-time applications required by the military, it may be possible to support soft real-time military applications.

7.0 CURRENT INVESTIGATIONS

DOM
Investigations at The MITRE Corporation are examining issues in migrating legacy C2 systems using DOM technology as an integration framework. In particular, the project is using a commercial DOM system to integrate subsystems in the Air Force's CTAPS system of systems.

The technical objective of the MITRE DOMIS project is to identify approaches for integrating legacy systems. We believe that OMG-compliant DOM technology can be used to provide an integration framework. To test our hypothesis, we are conducting a set of experiments. Important aspects of these experiments are the ease of coarsely encapsulating legacy applications and databases, the ease of refining this coarse encapsulation to provide a better integration of the legacy applications and databases, the applicability of the OMG object services to C3I systems, the identification of techniques for integrating databases that use different database management systems (for example, Sybase for intelligence and Oracle for C2) within the DOM environment, and the identification of techniques for integrating heterogeneous applications and databases with respect to data naming. Our technical objective also includes influencing vendors through our participation in OMG and recommending an acquisition approach based on a DOM system as an integration framework.

Improved System Administration (ISA)
Additional investigations are underway prototyping an ISA function. This ISA, based on commercial software, is eventually intended to provide a replacement for a uniquely developed system administration application. Using commercial software embracing open standards, an ISA is being prototyped at MITRE for the WCCS System using the commercial product Tivoli. Although this effort has been recently initiated in January 1995, we expect to witness improvements to end-user ease of use and to provide for a homogeneous system administration environment (e.g., user access, privileges, passwords, network, account, and security administration).

8.0 CONCLUSIONS

Increases in commercial technology will necessarily provide the potential to change many facets of C2 AISs. These increases have the potential to impact business practices, the operations (i.e., doctrine of C2 AISs), as well as the system architecture (i.e., hardware and software). A wider availability of commercial desktop computers with accompanying desktop application software has opened a new, and currently separate, world to many of the users of C2 AISs. The ability of desktop users to easily access and reuse information derived from commercial and military global sources (e.g., commercial data providers, Prodigy, America On Line) will create a need to provide this same capability in C2 AISs.

Providing global reuse and manipulation of data within C2 AISs presents several difficulties for the system designers and implementers. Discounting the obvious issues of data security and integrity, several issues involving the use of a desktop paradigm (e.g., distributed versus localized computing, complex relational data storage versus single element/single file storage) in C2 AISs must be resolved.

In order to prepare for the eventual changes, the government must get abreast and stay abreast of changes in the commercial marketplace. Additionally, the government should support continued investment in migration and legacy techniques:

- software reverse engineering to identify software component dependencies
- migration of software components to emerging open technologies
- encapsulation of legacy components utilizing DOM technology to allow their reuse until replacement.

Finally, the government should work at developing new cost models, including resourcing, scheduling, and commercial availability modules, which would give the program managers additional tools to aid in their migration planning.

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SIMULATION MODELS FOR IFF SYSTEM PERFORMANCE ANALYSIS

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SUMMARY

Identification Friend or Foe (IFF) is an important means of air traffic surveillance for military air operation. Due to this fact, several studies of IFF equipment were conducted in the past. To assist the analysis of IFF system performance, two simulation models have been developed at "ESG Elektroniksystem- und Logistik GmbH" in Munich, Germany. The description of these models is the main subject of this paper.

The first model is based on a probabilistic methodology. It operates on a scenario reflecting the environment to be considered. The model determines the interrogation rates at each transponder deployed in the environment. Applying probability theory, the behaviour of the transponders is predicted and their reply rates are obtained. The reply rates are the input for the calculation of the signal loads at the interrogators and the establishment of their behaviour.

The second model is designed as a discrete-event simulation model. At each point in time an interrogation is generated, the arrival times and the power levels of the interrogation at the transponders are determined. The processing of the interrogation by the transponders is modelled taking into account various interference mechanisms. If a reply is challenged by an interrogation, the arrival times and the signal power levels at the interrogators are calculated. Interferences with the reply are checked in order to establish the proper evaluation of the signal by the interrogator.

1. INTRODUCTION

IFF systems are utilised to identify friendly airborne platforms. IFF systems consist of interrogators and transponders. Interactions between these components are performed on the principle of question and answer. A question is generated by the interrogator as a coded electromagnetic signal and transmitted towards an airborne platform. An aircraft equipped with a transponder decodes the question and transmits a coded reply as a response. Finally, the reply is received and evaluated by the interrogator to obtain the identity of the aircraft.

The first IFF system was introduced in 1948. The system called MKX employed the interrogation frequency 1030 MHz and the reply frequency 1090 MHz. Three different coded interrogations were implemented, designated as Mode 1, Mode 2, and Mode 3, while only one unique reply signal was defined consisting of four pulses. All signals were pulse position modulated.

During the following years, the MKX system was improved by introducing a coder-unit within the transponder, which was able to provide additional reply information by generating variable coded replies. This coding capability was termed "Selective Identification Feature" (SIF). Therefore, the improved MKX system was named MKX(SIF).

Currently in use is the successor of the MKX(SIF) system, which is termed MKXA. The interrogation and reply signals of the MKXA system are pulse position modulated on a 1030 MHz (interrogation) and 1090 MHz (reply) carrier frequency. MKXA utilises the interrogation Modes 1, 2, 3/A, and C. For each of the Modes 1, 2, and 3/A, 4096 reply codes are available, which can provide identity information of an aircraft. Mode C is used for altitude reporting.

In order to increase the resistance of IFF against spoofing, exploitation, and jamming, a new cryptographic encoded feature designated as Mode 4 was added to the MKXA system during the 1960's. The resulting IFF, containing Mode 1, Mode 2 , Mode 3/A, Mode C, and Mode 4, has been called MKXII.

At the beginning of the 1980's, a common process has been initiated by different nations to define a NATO wide compatible IFF system based on modern technologies. The concepts for this future IFF system are termed NIS (Nato Identification System) and NGIFF (Next Generation IFF).

Because of the dependency on IFF for air traffic control and engagement purposes, several studies of contemporary IFF equipment (MKXA, MKXII) as well as future military identification systems (NIS, NGIFF) were conducted. The overall objective of these investigations was to establish a realistic basis for the assessment of the IFF system performance in dense environments.

Two simulation models for IFF system performance analysis are introduced in this paper. The models quantify the interference impacts at transponders and interrogators deployed in an environment and predict their behaviour. Although both models are suitable for IFF analysis, they differ with respect to the modelling philosophy. The first model is based on a probabilistic method applying statistical principles, the second consists of a discrete-event simulation program modelling the different occurrences within an IFF system. The description of these models is the main subject of this paper.

The paper is structured into 7 parts. Following this introductory section, section 2 contains a brief description of the main features of IFF systems. Section 3 discusses the environment model, which serves as input for the simulation programs. The probabilistic simulation model and the discrete-event model are described in section 4 and 5. Outputs of the models as well as conclusions and final remarks are the content of section 6 and 7.

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2. IFF SYSTEM DESCRIPTION

2.1 Generation of Interrogations

For transmission purposes an IFF interrogator is equipped with an antenna system consisting of a directional and a control antenna. The directional antenna is characterised by a main beam with high antenna gain and series of side lobes with lower gains. The control antenna is designed as an omni-directional pattern such that its gain is smaller than the main beam gain and greater than the major side lobe gain of the directional antenna.

An interrogator is triggered to generate interrogations periodically at a defined interrogation repetition frequency. The final decision, whether an interrogation is initiated, is controlled by the interrogation protocol. The current IFF systems MKXA and MKXII are using the protocol types continuous, automatic, autospecific, and manual. The respective definitions of these protocol types are as follows.

An interrogator utilising continuous protocol generates interrogations permanently independent of the presence of targets.

An interrogator operated with automatic protocol initiates interrogations each time a target is detected by the associated primary radar - irrespectively whether that target has been previously identified. The interrogation process is induced while the antenna main beam is sweeping across the target. During the sweep, a sequence of question and answer cycles is initiated, which is referred to as a burst.

Interrogators using autospecific protocol initiate an interrogation burst only for a target for which a recognised track is not held. Reinterrogation only occurs on track discontinuity.

An interrogator operated with manual protocol generates interrogations only when they are initiated by an operator.

When an interrogation has been generated by an interrogator, the signal is transmitted via the directional antenna. Beside the basic interrogation, an IFF interrogator transmits an additional pulse via the control pattern, which is called Interrogation Side Lobe Suppression pulse (ISLS-pulse). A transponder illuminated by the main beam receives the ISLS-pulse with a power below the interrogation transmitted via the directional antenna. In this case the transponder is said to receive a main beam interrogation. For a transponder located outside the main beam, the power of the ISLS-pulse is greater than the power of the basic interrogation. Therefore, the interrogation is termed a side lobe interrogation.

2.2 Processing of interrogations

An interrogation is received by a transponder via an omni-directional antenna. Various techniques like diversity and lobe switching are applied in order to achieve omni-directional antenna characteristics at an aircraft.

When an interrogation enters a transponder, the transponder starts to perform a set of procedures consisting of message recognition, processing, reply transmission, and recovery. The duration of these procedures depends on the transponder design.

An interrogation can only gain control of a transponder after the signal has been received successfully and recognised as a valid message. If the receipt of an interrogation interferes with the arrival of another signal such that they overlap, the interrogation may fail.

Once a valid interrogation has been obtained, the transponder enters the processing stage. The processing performs two main functions. The first function decodes the interrogation and determines whether it is a main beam or a side lobe interrogation.

If a main beam interrogation has been recognised, the second function is invoked, which produces a coded reply. At the end of the processing stage, the reply is transmitted via the omni-directional antenna of the aircraft. The reply transmission is followed by a time period which allows the transmitter to recover. From the beginning of the processing stage until the end of recovery, the transponder is suppressed. Each interrogation arriving during the suppression time is rejected and fails.

When a side lobe interrogation has been received, the transponder transmits no reply but falls also into suppression and does not accept any interrogation until the end of suppression.

2.3 Evaluation of Replies

An interrogator receives the replies created in response to its own challenges via the main beam of the directional antenna. Friendly Replies Unsynchronised In Time (FRUIT), which are replies from transponders elicited by other interrogators, may cause failure in correctly decoding an expected reply.

To reduce the impact by FRUIT, interrogators are equipped with a receiver side lobe suppression (RSLS). The receiver side lobe suppression is realised by applying on the receiving path a sum and a difference channel simultaneously. In general, the sum channel is connected with the directional antenna and the difference channel with the control antenna. The power levels of a reply received via both antennas are compared. If the sum channel produces a larger signal strength than the difference channel, the reply is accepted as a main beam reply. In the other case, the reply is designated as a side lobe signal and is ignored.

Based on the number of valid replies received from a transponder, the interrogator performs an evaluation process and displays the result on a plain position indicator (PPI).

3. ENVIRONMENT MODEL

The success of an interrogation-reply interaction between an interrogator and a transponder depends very heavily on the environment the IFF equipment is deployed in. Therefore, an IFF simulation program requires as an input an appropriate environment model, which reflects the density and the technical characteristics of interrogators and transponders. Such an environmental model is called a scenario.

A scenario is described by parameters, which can be broken down into the following classes:

- platform data (latitude, longitude, height, etc.),
- antenna data (antenna geometry, gains, etc.),
- transmitter-receiver data (frequency, transmitter power, sensitivity, etc.),

- signal generator data (modes, interrogation repetition frequency, etc.),
- prime sensor data (range, protocol type, etc.), and
- processor data (occupancy and processing times).

For the application of the two simulation models described in the following sections, these parameters have to be provided within separate files, each containing data records of a specific parameter class.

The establishment of a simulation environment is realised by a control file. The control file contains a list of those platforms which have to be considered in a simulation run. Technical data sets stored in the scenario files are assigned to each platform by reference numbers. This approach, as seen in Figure 1, provides a high degree of flexibility concerning the definition of a simulation environment.

4 PROBABILISTIC MODEL

The simulation model introduced within this section was developed originally for the NIS program. During the late 1980's the model was also used for the performance analysis of contemporary MKXA and MKXII equipment within the "Central European Study" conducted by NATO AC/302(SG/5)WG/4. In 1992 the model was upgraded to include the characteristics of NGIFF Mode 7 and Mode 8 and simulation runs were performed to support system performance analysis and investigations concerning frequency compatibility aspects.

The model is based on a probabilistic approach and can be functionally broken down into four parts:

- determination of interrogation rates,
- determination of transponder behaviour,
- determination of fruit rates, and
- determination of interrogator behaviour.

Within the following paragraphs these parts are described with special emphasis on the mathematical concepts applied within each step.

4.1 Determination of interrogation rates

Generally, the interrogation rate at a transponder is established by counting the arriving interrogations during a period of time and computing the ratio of the number of interrogations and the recording time. As the monitoring time increases, the interrogation rate gets into a steady state termed long-term interrogation rate.

In the simulation model the extent of interrogations at a transponder is characterised by the long-term interrogation rate. The model computes the long-term rates at all transponders deployed in the environment. Due to the ISLS-pulse, an interrogation is received by a transponder either as a main beam or as a side lobe interrogation. The time a transponder is occupied by a main beam interrogation differs from the occupancy time caused by a side lobe signal. Therefore, main beam and side lobe interrogations are recorded separately by the model.

At a particular transponder the interrogation rate is established in two steps. Firstly, the contribution from each interrogator is computed. Secondly, the total rate at the transponder is obtained. In order to shorten the description of these two steps, the following discussion will concentrate on main beam rates, but it should be noted that a similar approach is applied to the side lobe rate calculation.

The computation of the main beam interrogation rate produced by a single interrogator I at a transponder T is based on the following approach. Consider the events

A : T is illuminated by the main beam of I and
B : I is active.

If IRF denotes the interrogation repetition frequency of I, the main beam interrogation rate $MBIR$ produced by I at T can be calculated by

$$MBIR = P(A \cap B) \cdot IRF = P(A) \cdot P(B / A) \cdot IRF.$$

Thereby, $P(A)$ denotes the probability that T is illuminated by the main beam of I and $P(B/A)$ terms the probability that I is active while T is in the main beam of I. Since the activity of an interrogator depends on the protocol type, the conditional probability $P(B/A)$ is called protocol factor.

The calculation of $P(A)$ for fixed and rotating antennas is very simple. In case of a fixed antenna $P(A)=1$, if the azimuth angle from I to T is covered by the main beam, otherwise $P(A)=0$. If the interrogator is equipped with a rotating antenna, then

$$P(A) = \frac{MBW}{2\pi},$$

applies, where MBW denotes the antenna main beam width. Similarly in the case of a scanning antenna, the calculation of $P(A)$ is performed taking into account the size of the scanning sector, its orientation, and the azimuth angle from the interrogator to the transponder.

Concerning the calculation of the protocol factor, by definition

$$P(B / A) = 1$$

for continuous interrogators, which are active all the time.

An automatic interrogator becomes active, if a target detected by the associated primary sensor enters the main beam. The interrogator stops interrogating as soon as the target leaves the main beam. Ignoring the horrendous problem of building the primary sensor target detection performance into the model, the assumption is made that each target within the nominal range and height envelope of the primary radar will be detected. Based on this assumption, the number of targets is determined by the model and a function f of the pointing angle $\alpha \in [0, 2\pi]$ of the antenna boresight defined by

$$f(\alpha) = \begin{cases} 1, & \text{if at least one target is in the beam} \\ 0, & \text{else} \end{cases}$$

is established.

At any time $t \in [0, TMLD]$, where $TMLD$ denotes the duration the transponder T is illuminated by the main beam of I, the event

$B(t)$: I ist active at t

occurs, if a target detected by the prime sensor is within the main beam of I. It should be noted that the transponder T is not necessarily a primary target, since the IFF coverage may exceed the range of the primary sensor.

At time $t \in [0, TMLD]$ the antenna boresight is pointing to

$$g(t) = \alpha + \frac{MBW}{2} - t \cdot \frac{MBW}{TMLD},$$

where α denotes the azimuth angle form I to T and MBW the main beam width. By definition, the probability $P(B(t))$ that I is active at time t satisfies the equation

$$P(B(t)) = f(g(t))$$

for each $t \in [0, TMLD]$. Applying this equation and utilising the substitution $\gamma = g(t)$ yields

$$P(B/A) = \frac{1}{TMLD} \int_0^{TMLD} P(B(t))dt = -\frac{1}{MBW} \int_{a+\frac{MBW}{2}}^{a-\frac{MBW}{2}} f(\gamma)d\gamma .$$

Based on the function f, the last integral is evaluated by the model to obtain the main beam protocol factor for a automatic interrogator. A similar approach is applied concerning the protocol factor computation of autospecific and manual interrogators.

So far the calculation of the interrogation rate contribution from a single interrogator to a particular transponder has been discussed. The total interrogation rate at the transponder produced by all interrogators is obtained simply by summing up the individual contributions.

In addition to the interrogation rates, the model determines the power levels of the signals at the transponders taking into account transmitter power of the interrogator, cable losses on the transmitting and the receiving path, transmitter and receiver antenna gains, and propagation losses.

4.2 Determination of transponder behaviour

The model characterises the transponder behaviour by the parameters reply efficiency (RE) and reply rate (RR). The reply efficiency denotes the probability that an interrogation is received, processed, and replied by a transponder. The reply rate qualifies the average number of replies transmitted by a transponder per second.

The simulation model determines reply efficiency and reply rate of each transponder deployed in the scenario based on the following mathematical methodology.

Consider a transponder T exposed to a main beam interrogation rate of $MBIR$ interrogations per second. Furthermore, assume that at any time t an interrogation arrives at T. This interrogation is received, processed, and replied, if the transponder is not occupied by one of the $MBIR$ interrogations at the arrival time t .

The total occupancy time T_{oc} caused by an interrogation is defined as

$$T_{oc} = T_{rec} + T_{prc} + T_{rep} + T_{rcv},$$

where T_{rec} is the time required for the receipt of the signal, T_{prc} the processing time, T_{rep} the time of reply transmission, and T_{rcv} the transmitter recovery time. Taking into account the occupancy time, the transponder is not occupied at time t , if within the interval

$$\Delta T = [t - T_{oc}, t]$$

none of the $MBIR$ interrogations arrives. The probability for an arrival within ΔT is given by

$$p = \frac{T_{oc}}{1\text{sec}}.$$

Assuming that the probability of k arrivals ($0 \le k \le MBIR$) obeys a binomial distribution, the probability for no arrival within ΔT can be derived from

$$P_{MB}(0) = (1-p)^{MBIR} = \sum_{k=0}^{MBIR} (-1)^k \binom{MBIR}{k} p^k \approx 1 - MBIR \cdot p .$$

Since $p << 1$, the last equation is obtained by truncating all terms of higher order with respect to p.

If a side lobe rate is received by the transponder in addition to the main beam interrogation rate, the same approach yields the probability $P_{SL}(0)$ for an interrogation being not affected by a side lobe signal.

Combining the probabilities for main beam and side lobe impact, the model determines the reply efficiency by

$$RE = P_{MB}(0) \cdot P_{SL}(0).$$

The reply rate of a transponder, which is an essential input for the determination of fruit rates at an interrogator, is derived from the equation

$$RR = MBIR \cdot RE.$$

4.3 Determination of fruit rates

An identification process, in which an interrogator and a transponder is involved, takes place during the sweep of the interrogator's main beam across the transponder. Replies, which are transmitted by other transponders during the sweep, may interfere with the replies of the transponder of interest in the beam. These replies are termed FRUIT.

Based on the reply rates of the transponders, the model calculates the fruit rates that may affect an identification process between an interrogator and a transponder. Due to the RSLS-function, a reply is received by the interrogator either as a main beam or as a side lobe signal. To take care of this fact, main beam and side lobe replies are recorded separately.

In order to shorten the discussion on fruit rate calculation, the following description will concentrate on main beam rates. However, a similar approach is implemented in the model for side lobe fruit computation.

Consider an interrogator I and a transponder T involved in an identification process. Additionally, assume a potential interfering transponder T_{intf} with a reply rate RR. Based on the events

A : T is illuminated by the main beam of I and
B : T_{intf} is within the main beam of I,

the main beam fruit rate, produced by T_{intf} and received by I while interrogating T, is given by the equation

$$MBFR = P(B/A) \cdot RR .$$

The term $P(B/A)$ denotes the probability that the interfering transponder T_{intf} is within the main beam of I while sweeping across T. This probability is computed by the model as a function of the azimuth angles from I to T_{intf} and T taking into account the main beam width of I.

The total fruit rate produced by all interfering transponders is calculated by summing up the individual contributions.

In addition to the amount of fruit, the power levels of the signals at the interrogator are determined. The parameters transmitter power of the transponder, cable losses on the transmitting and the receiving path, transmitter and receiver antenna gains, and propagation losses are included in the power calculation.

4.4 Determination of interrogator behaviour

The performance of an interrogator is characterised by the parameters decode efficiency (DE), round trip reliability (RTR), and probability of identification (PID).

The decode efficiency denotes the probability that a reply is received and decoded by the interrogator. Generally, a reply is received and decoded, if it is not overlapped by fruit replies. In case of overlapping, a reply may be decoded, if the signal to interference ratio does not exceed a decoder specific limit.

The calculation of the decode efficiency is performed in the following fashion. Consider an interrogator I and a transponder T. Let FR denote the total fruit rate, consisting of main beam and side lobe fruit, received by I during interrogating T.

Just to simplify the description, assume that the fruit replies and a reply from T have the same signal length T_{rep}. In that case, the probability that a reply of T is overlapped by k fruit replies ($0 \le k \le FR$) can be computed by applying the binomial distribution function

$$p(k) = \binom{FR}{k} \left(\frac{2 \cdot T_{rep}}{1\text{sec}}\right)^{k} \left(1 - \frac{2 \cdot T_{rep}}{1\text{sec}}\right)^{FR-k}.$$

The application of the binomial distribution is based on the assumption that the fruit replies are statistically independent.

Again to simplify the description, assume that all fruit replies arrive with the same power level PL given in dBm. The total interfering energy within a reply of T, produced by k ($0 \le k \le FR$) overlapping fruit replies, is derived from

$$I(k) = 10 \cdot \log(k \cdot 10^{\frac{PL}{10}}).$$

Generally, the probability for decoding a reply can be deduced from a detection curve $d(S/I)$, which is a function of the signal to interference ratio. The slope of the curve depends on the decoder design and can be obtained by measurements.

Utilising the detection curve, the model computes the probability for decoding a reply of T, arriving at the interrogator with a power level S, by the equation

$$DE = \sum_{k=0}^{FR} p(k) \cdot d(S / I(k)).$$

Based on the reply efficiency of a transponder and the decode efficiency, the success of a full interrogation-reply interaction is characterised by a parameter called round trip reliability (RTR). The round trip reliability is given by

$$RTR = RE \cdot DE.$$

Taking into account the evaluation criteria of an interrogator, the probability of identification is derived by the model as a function of the round trip reliability.

5 DISCRETE-EVENT MODEL

The simulation model introduced within this section was developed during 1994 primarily to enable the evaluation of the mutual interference arising from interactions between Mode S and IFF systems. The interspersion of Mode S transactions with IFF reply-requests, combined with the aperiodic Mode S interrogation schedule, directed the model development effort to a discrete-event simulation. Although the model relates mainly to Mode S, it is also capable to analyse the performance of IFF systems.

The software of the model is coded in MODSIM II, a modern language for object oriented programming with special capabilities for discrete-event simulation. The model is running on a HP Workstation under UNIX.

Since the simulation model is based on an object-oriented approach, its structure will be discussed utilising the "Object Modeling Technique" (OMT) as presented in [3]. This methodology allows to consider the model from three related but different viewpoints, each capturing important aspects. In accordance with these three viewpoints,

- the object structure,
- the functional structure, and
- the dynamic structure

of the discrete-event model are described within the following paragraphs.

5.1 Object Structure

Objects are data structures coupled with routines called methods. Attributes in the object's data structure define the state of an object at any instant in time while its methods describe the actions which an object can perform to change the states. The attributes and the methods of an object are collectively referenced as its properties.

An object class describes a group of objects with the same attributes and methods, but each object in a class has its own identity and its own values for the attributes.

To promote understanding of the real world, the basic object classes

- interrogator,
- transponder,
- interrogation, and
- reply

have been defined for the discrete-event model.

Since in reality an interrogator and a transponder represent an assembly of different components, the object classes interrogator and transponder are defined by an aggregation of further detailed objects. An interrogator for instance consists of a platform, antenna, transmitter-receiver unit, signal generator, primary sensor, and decoder object. A transponder is composed of a platform, antenna, transmitter-receiver unit, and processor object.

Figure 2 contains the object diagrams of the interrogator and transponder object class, which reflect the aggregation relationships.

5.2 Functional Structure

The functional structure of the discrete-event model is determined by the processes which are driven by the objects involved in the simulation. The basic processes are:

- generation of interrogations,
- propagation of interrogations,
- processing of interrogations and generation of replies,
- propagation of replies, and
- evaluation of replies.

Figure 3 illustrates the functional structure of the discrete-event simulation program. The processes are drawn as ellipses. The objects driving a process are attached to the graph.

5.3 Dynamic Structure

The discrete-event simulation program models a sequence of processes which are challenged by the activities of the objects. Since many objects are involved in the simulation at any instant of simulation time, multiple concurrent processes can occur. To keep track of all these processes, the programming language MODSIM II, which is utilised for the discrete-event model, keeps a pending list. This pending list is an ordered list of all objects which have scheduled activities. The object with the most imminent activity is ordered first in the list. Once the activity of an object scheduled for a particular instant of simulation time has been carried out, the simulation clock is advanced to the next point in simulation time, when the next activity of an object has been scheduled.

The dynamic structure of the model is determined by the time dependent activities of the objects which are driving the processes specified in the functional structure. In the following paragraphs these processes are described in more detail with special emphasis on the dynamic behaviour of the involved objects.

5.3.1 Generation of Interrogations

The process of generating interrogations is driven by the signal generator object in conjunction with the primary sensor object of an interrogator.

To model the dynamic behaviour of a primary radar, a state variable is assigned to the primary sensor object. For a continuos interrogator, the state variable is set to "active" during the total simulation time. In case of an automatic interrogator, the initial state of the variable is "passive". The variable becomes "active" each time a target enters the main beam. It is reset to "passive", when no longer any target is illuminated by the antenna main beam. In case of an autospecific and a manual operated interrogator, it is randomly decided whether the state is set to "active" when a target enters the main beam. For the purpose of determining the targets of an interrogator, an ideal primary sensor is assumed able to detect each target within the coverage.

The first time a signal generator is triggered to generate an interrogation is determined randomly. As soon as the simulation clock is advanced to this point in simulation time, the state variable of the associated primary radar is checked. If the state is set to "active", the interrogation is generated, otherwise the interrogation is suppressed. In the case of generation, a new instance of an interrogation object is created. Then the signal generator waits for the next time to be triggered. This loop is repeated until the simulation end is reached.

The state diagram within Figure 4 illustrates the dynamic model of the signal generator concerning the generation of interrogations. The different states are drawn as rounded boxes. The conditions that have to be fulfilled for a transition from one state to another are attached within square brackets.

5.3.2 Propagation of interrogations

When an interrogation has been generated by an interrogator, a new instance of a interrogation object is created by the simulation model. The purpose of the interrogation object is to model the propagation of an interrogation and its arrival at transponders.

The propagation times are determined, which are required by the interrogation to travel from the generating interrogator to the transponders deployed in the environment. The transponders are stored in an ordered list with respect to the propagation times. The arrival of the interrogation at the closest transponder is scheduled first. When the simulation clock is advanced to this point in time, a message is sent to the associated processor of the transponder. If there are further transponders, the arrival at the next transponder is scheduled. This cycle is repeated until the interrogation has arrived at all transponders in the environment.

In case of arrival, the signal strength of the interrogation at the transponder is computed including the parameters transmitter power, cable losses on the transmitting and the receiving path, transmitter and receiver antenna gains, and propagation loss. The power levels are calculated for the basic interrogation as well as for the corresponding ISLS-pulse.

5.3.3 Processing of interrogations

The processing of interrogations is performed by the processor object assigned to each transponder.

Initially, the processor object of a transponder is in the state "not occupied" and thus, ready to receive and process interrogations. As soon as an interrogation arrives at a transponder with a power level above the receiver sensitivity, a check is performed to determine whether the interrogation is received without any interference. This check includes the possibilities that the transponder is occupied by a previous interrogation or that the transponder is receiving another interrogation, thereby, causing overlapping of the signals. In case of an occupied transponder, the arriving interrogation fails and does not change the current state of the processor. If two signals overlap during the receipt, it depends on the power levels of the signals whether one of the interrogations may succeed. If neither of the interrogations can be successfully received, it is because they are said to be garbled. The resistance to garble depends on the transponder design and can be analytically expressed in terms of a detection curve. The detection curve of a transponder can be integrated into the processor model.

When an interrogation is successfully received, it is checked whether a main beam or a side lobe signal has been recognised. Main beam and side lobe interrogations are distinguished by comparing the power levels of the interrogation and the corresponding ISLS-pulse.

In the case of a side lobe receipt, a suppression time is induced. During the time of suppression, the processor is in

the "occupied" state and does not accept any interrogation. At the end of suppression, the state of the processor is reset to "not occupied" and new interrogations are accepted.

Having received a main beam signal, the transponder becomes "occupied" too and can not be accessed by an interrogation until the state is changed to "not occupied". During the occupancy time, the received interrogation is processed. When the simulation time has advanced to the end of the processing stage, the corresponding reply is transmitted. As a consequence, a new reply object is created. As soon as the time required for transmission is elapsed, an additional recovery time is provided and at its end the state of the processor is set to "not occupied", thereby, being ready to accept a new interrogation.

The dynamic model of the processor object is shown by the state diagram in Figure 5.

5.3.4 Propagation of replies

Each time a transponder transmits a reply, a new instance of a reply object is created by the simulation model. The purpose of the reply object is to model the propagation and the arrival of replies at interrogators.

The propagation times are determined, which are required by the reply to travel from the generating transponder to the interrogators involved in the simulation. The interrogators are stored in an ordered list with respect to the propagation times. The arrival of the reply at the closest interrogator is scheduled first. As soon as the simulation clock is advanced to this point in time, a message is sent to the associated decoder of the interrogator. If there are further interrogators in the ordered list, the arrival at the next interrogator is scheduled. This cycle is repeated until the reply has arrived at all interrogators.

For each arrival, the signal strength of the reply at the interrogator's receiver is calculated based upon the transmitter power, the cable losses on the transmitting and the receiving path, the transmitter and receiver antenna gains, and the propagation loss. In the case of an interrogator equipped with a receiver side lobe suppression (RSLS), the power levels of the reply, received via the sum and the difference antenna, are determined.

5.3.5 Evaluation of replies

The decoding and evaluation of replies is modelled by the decoder object assigned to an interrogator.

When a decoder gets a message indicating the arrival of a reply, the receiving procedure is started. An interference check is made against other replies. If the reply is overlapped, the power levels of the overlapping signals are compared. Based on the detection curve of the decoder, which provides the probability of detection as a function of the signal to interference ratio, it is determined whether the reply is detectable. A reply unable to be decoded is ignored.

If the decoder is capable to detect the reply and if the interrogator is equipped with a receiver side lobe suppression (RSLS), a comparison of the power levels received via sum and difference antenna pattern is performed. If the reply turns out to be received via the side lobes, the signal is not further processed.

A main beam reply, successfully received and decoded, is correlated with the generating transponder and a reply counter is updated. As soon as the sweep of the interrogator's antenna main beam across this target is completed, the number of received replies is evaluated. Taking into account the evaluation algorithm of the interrogator, the code detection or the identification is declared.

The dynamic behaviour of a decoder object is illustrated within the state diagram in Figure 6.

6. MODEL OUTPUTS

Both models introduced in the previous sections provide graphical outputs of the simulation environment and results.

The simulation environment is displayed reflecting positions and types of the platforms deployed. A map can be inserted containing geographical information like borders, coastlines, rivers, or cities.

At the end of a simulation run, the operational area and - if relevant - the operational sectors of an interrogator can be displayed. Optionally, all targets within the operational coverage or only a subset of targets can be inserted.

A subset may be determined by any criteria. Typical criteria are for instance predefined limits for probability of identification, reply efficiency, or any other parameters. In case of a given criteria, only the targets are displayed which do not fulfil the criteria. Labels can be attached to each target indicating the identity or any other information of the aircraft.

Concerning simulation results, statistics gathering is accomplished by the models for a variety of parameters. The most important parameters, which can be used as measures of IFF system performance, are:

- main beam and side lobe interrogation rates,
- reply efficiency and reply rates,
- main beam and side lobe fruit rates,
- decode efficiency, and
- probability of identification.

The models perform statistical evaluations of these parameters providing maximum, minimum, mean value, standard deviation, and distribution function. The statistical data are displayed in graphical form.

As a special feature, the discrete-event model is capable of graphical animation, which promotes the understanding of the dynamic behaviour of the various objets involved in the simulation. The generation of interrogations, their arrival at the transponders, the generation of replies, and the arrival at the interrogators are displayed.

7. CONCLUSIONS AND REMARKS

This paper has focused on the introduction of two simulation models for IFF system performance analysis.

The first model is based on a probabilistic approach. It depends on the application of statistical laws. Some assumptions are made like the statistical independence of interrogations and replies, which are valid for dense signal environments. Due to this fact and because the program is

very cheap in computing time, the model is primarily suitable to handle large scenarios.

The second model is designed as a discrete-event simulation program. This methodology is capable of very accurate results, given good quality equipment data and propagation calculation algorithms. However, it is more expensive in computing time.

Finally, it should be mentioned that both models are not only applicable to explore the effects of self-interference caused by interrogations and fruit. The models can also be utilised for the analysis of ECM impact on the IFF system performance. Furthermore, problems concerning frequency compatibility aspects of IFF with civil SSR systems can be investigated.

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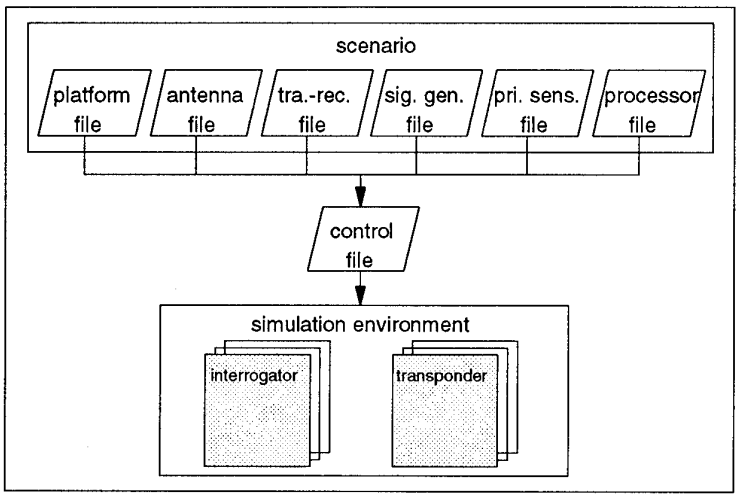


Figure 1: Establishment of a simulation environment

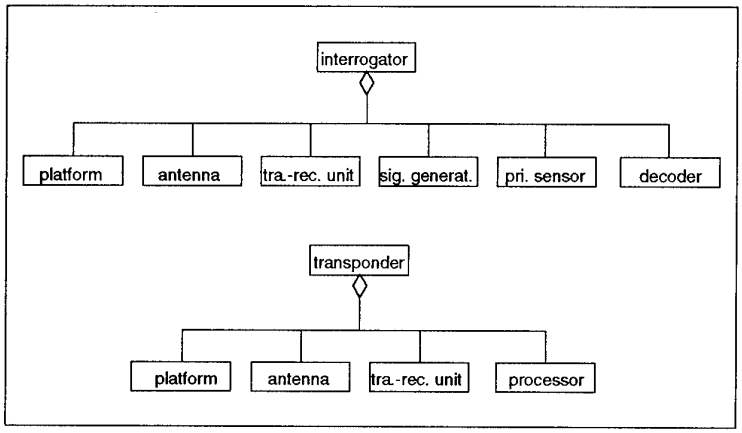


Figure 2: Object structure

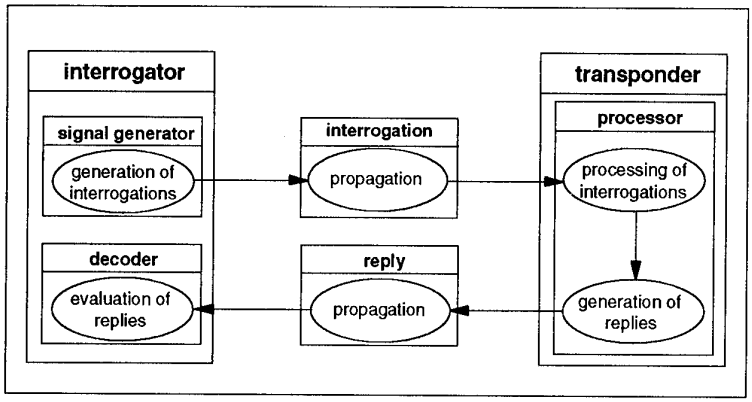


Figure 3: Functional structure

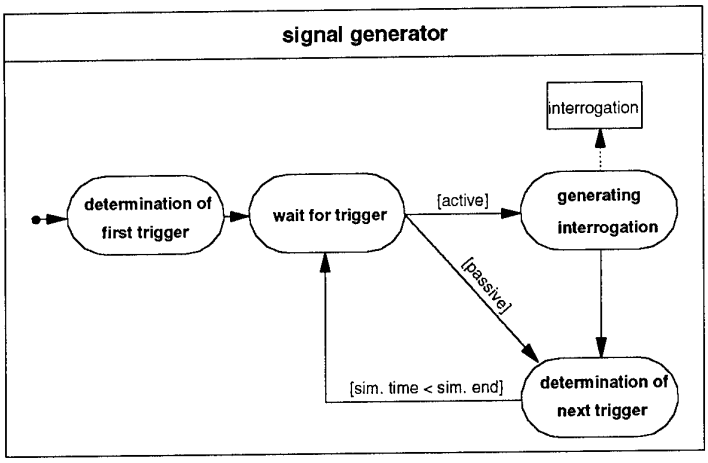


Figure 4: Dynamic structure of signal generator

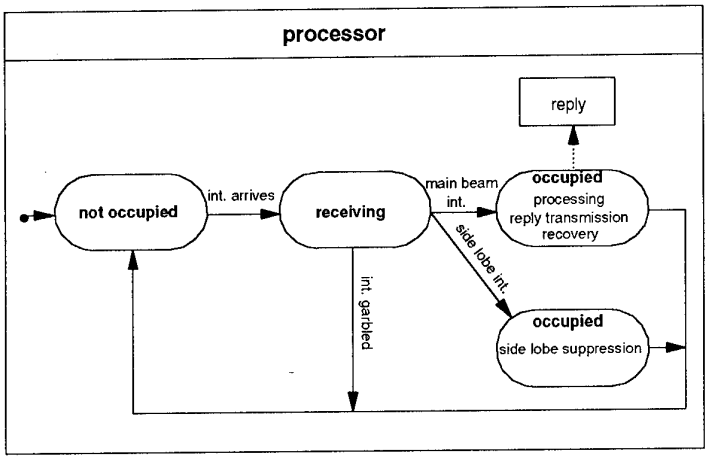


Figure 5: Dynamic structure of processor

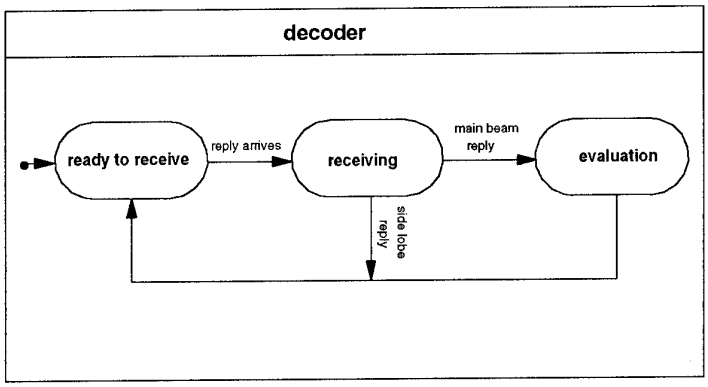


Figure 6: Dynamic structure of decoder

Applications of Multisensor Data Fusion to Target Recognition

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Abstract

Target Recognition, which is a key function for ensuring the successful execution of conflicts and wars, will be based on multisensor data fusion. For instance, the recent developments concerning the future Surface-Air surveillance and tracking systems design are based on the use of both multifunction sensors and integration of data coming from sensors such as Radars, Infra Red Search and Track, Electronic Support Measures and Electro-Optical devices.

The performance and reliability of target recognition is improved by making the best use of both complementarity and redundancy between sensors.
Redundancy allows validation of target class membership assessment while complementarity gives access to a variety of parameters which refines the recognition level, improves the target discrimination performance and/or reduces the time needed to achieve a given recognition performance.

An efficient multisensor recognition system must make the best use of several kinds of informations; basically one can distinguish:

. instantaneous physical properties of the target such as target Radar Cross Section, Doppler spectrum or High Resolution Range Profile for a radar, angular extent and/or image texture for an IRST, waveform parameters (such as carrier frequency, pulse repetition interval and pulse lenght) for an ESM,

. target behaviour properties such as the velocity, acceleration, rate of climb or style of manoeuvre (such as "terrain following" or "pop-up").

The first kind of knowledge relies mainly on sensor waveform generation, signal processing and extraction expertise, while the second is more a matter of mastery of data processing and multisensor tracking.

Fusing these informations means that one must process the data both spatially (e.g. from different sensors or from different parameters extracted from the same sensor) and temporally (e.g. from scan to scan or frame to frame) which implies that the recognition function must be perceived as a dynamic process.

Together with processing these data in order to optimise the recognition performance, the recognition system can participate to improve :

. sensors performances by optimising the sensor signal processing and ecxtraction according to the supposed target type (as for instance optimising the Constant False Alarm Ratio processing according to the target size),

. data processing (multisensor tracking) by giving new capabilities for track initiation, plot-to-track and/or track-to-track correlation,

. overall system efficiency by managing the sensors ressources (as for instance by requesting the necessary waveform at the useful time) in order to optimise the trade-off between the recognition performance and the system overall load/Low probability of Intercept property.

The preceeding remarks together with more practical considerations such as data flows and data structures show that, even if the data to process and the processing methods are different, target tracking and target recognition must be performed in tight cooperation.

The objective of this paper is to highlight some aspects of multisensor data fusion applied to target recognition in the aim of defining an operational system.
After having introduced the subject, the paper gives a description of a multisensor system and processing architecture which can be used for simultaneous target recognition and tracking.

Basic fusion techniques such as Bayesian Inference, Evidence Theory and Fuzzy Logic are then introduced, some practical results being

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presented for illustrating these techniques.
Finally a data processing architecture including both tracking and recognition functions is presented and respective merits of conventional techniques are discussed with regard to the different processing functions.

1. INTRODUCTION

Complex situation assessment systems require more and more precise informations for maintaining the necessary level of security. This is the case for Military Control and Command systems such as Air Defence Centers, Combat Management Systems for maritime forces or Battlefield Command Systems, but also for civil applications such as Air Traffic Management or Airport Surface Control.

All of these systems rely on the same generic elements :

- sensors to detect, locate and identify the objects,
- communications to transfer data from sensors to centers and commands from centers to sensors,
- control centers where data are merged and analysed and where decisions are made regarding the situation as it is perceived,
- defence systems and/or control procedures as decided by the authority.

Recent events have highlighted a very strong demand in terms of identification, mainly to avoid fratricid actions. Identification normally relies on specific sensors (IFF) or procedures (flight plans), but complex situations may require more complete identification means involving non cooperative sensors as well.

Such considerations led to view data fusion as a function in which positional and identification data are to be processed together.

2. MULTISENSOR SYSTEM DESCRIPTION

2.1 Technical functions

The main technical sub-functions of a multisensor data fusion system are summarized below:

Data acquisition : this function is necessary to acquire the sensor output and manage an associated memory; it acts as an interface between sensors and the data fusion system.

Data alignment: it is necessary to transform the data (plots and/or tracks) output from various sensors into a common coordinate and time frame. Data alignment is the key function on which lies the data fusion principles (synchroneous, asynchroneous or hybrid update); it must be used for transforming the quality informations (e.g. standard deviations) as well.

Track initiation: the objective of the data fusion is to supply a unique track for each object being detected by any sensor of the system, it is then necessary to initiate this track from either plots or tracks supplied by the sensors. In general some time integration is used when false alarm reduction is required. In order to optimise track initiation in a multisensor system one must therefore take in account the false alarm characteristics of each sensor.
In order to improve the track initiation in a dense environment and also when data from different sensors are used simultaneously, track initiation must rely on both positional and identification (if available) data.

Correlation: this function is used to determine wether a new sensor data corresponds to an existing (multisensor) track, it is mainly based on gating logic for coarse correlation and more refined algorithms using data accuracies for fine correlation. It must be performed after data alignment (which can consist to update the track to the new data time or conversely).

Association: in a dense object environment and/or for high false alarm rate sensors, several correlations can be possible (several plots for the same track or several tracks for the same plot or both cases). In this situation one must use a decision algorithm based on some association likelihood assessment; the choice of this algorithm can have a strong impact on the data fusion structure (see "track maintenance"), the simplest methods are based on a "Nearest Neighbour" approach while more sophisticated "Multi Hypothesis Tracking" techniques becomes now available. Again, if identification data are available, they must be used for reducing the risk of possible wrong association.

Track update: it is performed to generate the new track state using the new data associated to the track. It is in general performed in a recursive way, using some kind of Kalman filter which is well suited to manage variations in both accuracies and sampling time.
However, targets may have sudden changes in heading and speed which can require some state adaptation in the Kalman filter; current methods range from the simplest (Variable State Noise filter) to more sophisticated ones (Interacting Multiple Model, for instance).
Identification data can be updated in the same way as more conventional positional data. However the updating techniques are different and depend strongly on the nature of the available data (see below).

Track maintenance: it is dedicated to track file management, allocation of track numbers, track deletion and memory management.

2.2 Architectures

Depending on several factors such as the type and number of sensors, communication constraints or system complexity, multisensor architectures may vary from decentralized systems where each sensor processes as much data as possible in order to send the fusion center as little data as possible up to centralized structures where raw sensor data are massively processed by the fusion center.

In terms of identification data, a decentralized architecture requires that each sensor proceeds to some level of analysis concerning the target nature, which means that the fusion center deals with merging symbolic data. A centralized system is a system where raw data are transfered to the fusion center which can merge such numeric data from different sensors before taking a decision about the target nature.

Even for a centralized architecture, it can be more efficient to process data at the sensor level; this is the case when contextual knowledge must be handled in order to analyse the results. An example is given by the High Resolution Range Profile produced by a coherent radar ; for extracting useful informations from such profile one must know informations such as clutter environment, waveform parameters, Doppler and Range filter parameters,... All of these informations are to be transferred with the profile if the fusion center wants to analyse its content. As long as that increases the data flow without improving the expected result it seems worthwhile to process the Range profile at the radar level in order to extract the relevant characteristics for target recognition.

Time integration is also a factor on which target recognition must be based, especially when such a precise identification is required that it implies a dynamic process with sensor management for instance.

A generic multisensor architecture is presented in Figure 1. This figure shows three main components which participates to target recognition:

- a local features fusion, located at the sensor level; this function supplies local declarations to the fusion center,
- a centralized features fusion, located at the fusion center level ; this function processes local features (after alignment) and supplies « instantaneous » declarations.
- a centralized declaration fusion, which is the core of the identification function and which (recursively) merges all sources of recognition in order to supply the best result at the current time.

3. IDENTIFICATION DATA FUSION TECHNIQUES

Among the numerous existing techniques for merging identification data, recent analysis refer to three main methods :

3.1 Bayesian techniques

It is the most common method, based on conventional probability description. It requires some a priori knowledge onto the problem to solve (conditional probability density functions, a priori probabilities and decision costs), it can be used for both continuous and discrete data and can relatively easily be structured for a recursive implementation.

If some decision is required, it can be viewed as a two steps methods: class probability evaluation then decision making procedure.

Bayes method assumes that an object can belong to one (and only one) class among N.
If a measurement (x) is made by the sensor, the "a posteriori" probability P(I/x) that the object

belongs to class I is given by the relationship :

$$P(I/x) = \frac{P(x/I).P(I)}{\sum_{J} P(x/J).P(J)}$$

Two different informations are then necessary:

- "a priori" conditional probability density functions P(x/J)
- "a priori" probabilities P(J)

If a decision is to be taken, Bayes introduced the notion of "decision cost" C_{IJ} which represents the cost one has if one decides that the class is I if it was J in reality.
The resulting class will be K if it minimizes:

$$C_k = \sum_I C_{KI} . P(I/x)$$

Bayesian technique can be used for merging different measures (x may be a vector), it can also be used to merge discrete data (x may be a vector of decision, the a priori conditional probability density functions are then equivalent to confusion matrices).

It will be shown below that it can also be used for a recursive identification integration.

3.2 Evidence Theory

Developped by Shafer and Demptser, it relies on some uncertainty description and is based on a more general class description (called the "frame of discernment") than the Bayesian ones; here one also considers every disjunction of classes in addition to the elementary ones.
A "mass" is assigned to each elementary proposition in order to represent the confidence one has for this proposition ("support" and "plausibility" are also used to represent the degree of belief).

Rules of combination are provided for merging data from several sources of knowledge (for instance several sensors or several sources of the same sensor).

The core of Evidence Theory is the "rule of combination" of informations supplied by two sensors. It is assumed that each sensor supplies a set of "masses" m(Pj), where Pj is an element of the frame of discernment. The result of the combination is given by :

$$m(P_k) = \sum_{I,J} m_1(P_I).m_2(P_J) / (1 - X)$$

In the above relationship, (I,J) is such that P_K is the intersection of P_I and P_J, and X is given by :

$$X = \sum_{I,J} m_1(P_I).m_2(P_J),$$

where (I,J) is such that the intersection of P_I and P_J is the empty set.

3.3 Fuzzy logic method

This method is also used when some uncertainty is to be taken into account regarding the problem to solve. It relies mainly on two basic functions: a "Membership Function" used to described how a given class can be represented on the basis of a given attribute, and a "Possibility Distribution" which describes how the actual value of a given attribute can be distributed when some measurement of this attribute is available.

From these elementary functions one can derive a "Possibility" and a "Necessity" which describe the confidence and uncertainty related to this attribute. Merging different attributes is done with simple computations such as "min" and "max" functions, using relative weights on each attribute.

The merging procedure can be done in a recursive way; this technique can be used for merging different kind of data (continuous, discrete, logical, already "fuzzied",...) and is well suited when no learning phase is possible (for instance kinematic data based recognition) and for sensor error measurement handling (using the possibility distribution).

The basic fuzzy logic relationship are summarized below:

For a given parameter (X_i), one knows the functions $M(x_i)$ and $D(x_i)$ which represent respectively the Membership Function and the Possibility Distribution. From these functions one can compute the Possibility (P_i) and Necessity (N_i) according to:

$$P_i = \underset{xi}{Max}\left\{Min\left[M(x_i), D(x_i)\right]\right\}$$

$$N_i = \underset{xi}{Min}\left\{Max\left[M(x_i), 1 - D(x_i)\right]\right\}$$

The fusion of several results is obtained by using different logical inference(conjunction or disjunction) and different weightings (W_i).

The weighted conjunction leads to:

$$P = \underset{i}{Min}\left\{Max\left[1 - W_i, P_i\right]\right\}$$

$$N = \underset{i}{Min}\left\{Max\left[1 - W_i, N_i\right]\right\}$$

The weighted disjunction gives:

$$P = \underset{i}{Max}\left\{Min\left[W_i, P_i\right]\right\}$$

$$N = \underset{i}{Max}\left\{Min\left[W_i, N_i\right]\right\}$$

4. APPLICATION TO IDENTIFICATION DATA FUSION

Introducing identification in a multisensor fusion system leads to design a new fusion architecture in which identification data :

- . is time updated,
- . is used for improving the plot to track association,
- . can be completed by extracting knowledge from kinematic data.

Figure 2 shows a typical diagram of fusion algorithm taking in account the above functions. This diagram assumes some local (sensor) Bayesian classification, each plot containing some positional and class data (Xp, Cp), the tracking output being represented by (Xt, Ct).

Possible implementation of sub-functions are detailed hereafter.

4.1 Recursive identification update

At a given time k, assuming that the tracked target can belong to a class I among N possible classes, one needs to evaluate:

P(I / Cpk), where Cpk represents the set of elementary decisions (Cp(1), Cp(2),..., Cp(k))

It can be shown that P(I / Cpk) can be written in a recursive form (if elementary decisions are independant):

$$P(I / C_{pk}) = \sum_I P(I / C_{pk-1}).P(C_p(k) / I) / D$$

where P(Cp(k) / I) is an element of the confusion matrix corresponding to the decision Cp(k) (current decision), and D is the normalization factor :

$$D = \sum_J P(J / C_{pk-1}) P(C_p(k) / J)$$

This procedure is illustrated on Figure 4 which represents the probability of classification as a function of time, for a situation involving four different targets. Confusion matrices (see Figure 3) are issued from radar experimental results obtained by a short term Doppler analysis of four different helicopters (two cases are showed depending on the type of signal analysed -blade flash or hub-).

It was assumed that for each helicopter the observation sequence was the same (four times a hub signal and one time a blade flash signal). It is also assumed that the classifier could give its confusion matrix for each decision; each helicopter type had the same a priori probability (0.25).

It can be seen that for each case the recursive integration allowed the decision to converge to the right one and that accurate decisions (such as these obtained on a blade flash) could greatly improve the result (see for instance target type 2 at scan 6). This shows that fusion quality strongly relies on a good knowledge of input data quality (such as the confusion matrix in the above case).

4.2 Plot-to-track identification data association

In a dense environment, plot to track association can be improved when identification data are available for both plots and tracks.
Basically the plot to track association is based on some likelihood assessment using positional data (for instance the Kalman innovation).
Using both positional and identification data needs to use the same kind of normalised "distance", the most logical choice being the probability (which can be easily computed for positional data).

Again assuming that both plots and tracks contain a class information (Cp and Ct as suggested above), one can compute the "class distance" as being the probability Pc that the plot and the track belong to the same class. Assuming that each class has the same a priori probability, one finds the following result:

$$P_c = \sum_I P(I / C_{pk-1}).\left[P(C_p(k) / I) / D\right]$$

where D is the normalisation factor :

$$D = \sum_J P(c_p(k) / J)$$

This relationship can be generalised to the multiplot and mutitrack case by simply evaluating every plot to track probability.

It can be seen that evaluating these probabilities leads very simple computations compared to the equivalent positional data probabilities. Introducing identification for improving plot to track association corresponds to only a very limited increase in algorithm complexity.

4.3 Kinematic data identification

Target spatial behaviour (such as altitude, speed, acceleration, rate of climb, ..) obviously contains information relative to the target type. Extracting this information is somehow difficult mainly for two reasons:

- target behaviour can not be «learned» in the conventional sense. This means that one must use some specific knowledge representation instead of measurement based statistics,
- kinematic data are supplied by a tracking algorithm and can be strongly corrupted by measurement noise.

Fuzzy reasoning gives answers to these two points and is then certainly a good candidate for kinematic data identification.

The Membership Function (see M(Xi) in 3.3 above) is used to define the possible values which can be taken for a given class, while the Possibility Distribution is used to describe the possible actual values when one has a measured value and its accuracy.

Figure 5 illustrates the basic fuzzy logic mechanisms with one class (C), one parameter (x) and one measurement (x_o, σ_o).

5. CONCLUSIONS

Introducing target identification in future multisensor systems is one of the keys to achieve the level of security required by complex situation assessment such as conflicts and wars, but also for civil applications such as Air Traffic management.

An analysis of how this introduction can be made shows that:

- identification fusion architecture can be designed in the same way than positional fusion architecture,
- identification fusion must be seen as a process involving both "spatial" and "temporal" merging,
- it is essential to supply the quality of the data to be merged (for instance a standard deviation, a probability vector, a confusion matrix, a Dempster-Shafer mass,..) together with the data itself,
- among existing techniques, Bayes methods and Fuzzy logic are prime candidates, Evidence Theory is promising but still requires some analysis effort concerning the "mass" assigment in a real sensor environment,
- there is no "best choice" of a technique among others, but the need to apply the "good" technique to solve each specific problem. Challenge is then rather to develop fusion systems where different techniques are used together and exchange data,
- R&D efforts are to be put on both exchanges between techniques, input data characterisation methods, and reference data base collecting are modeling.

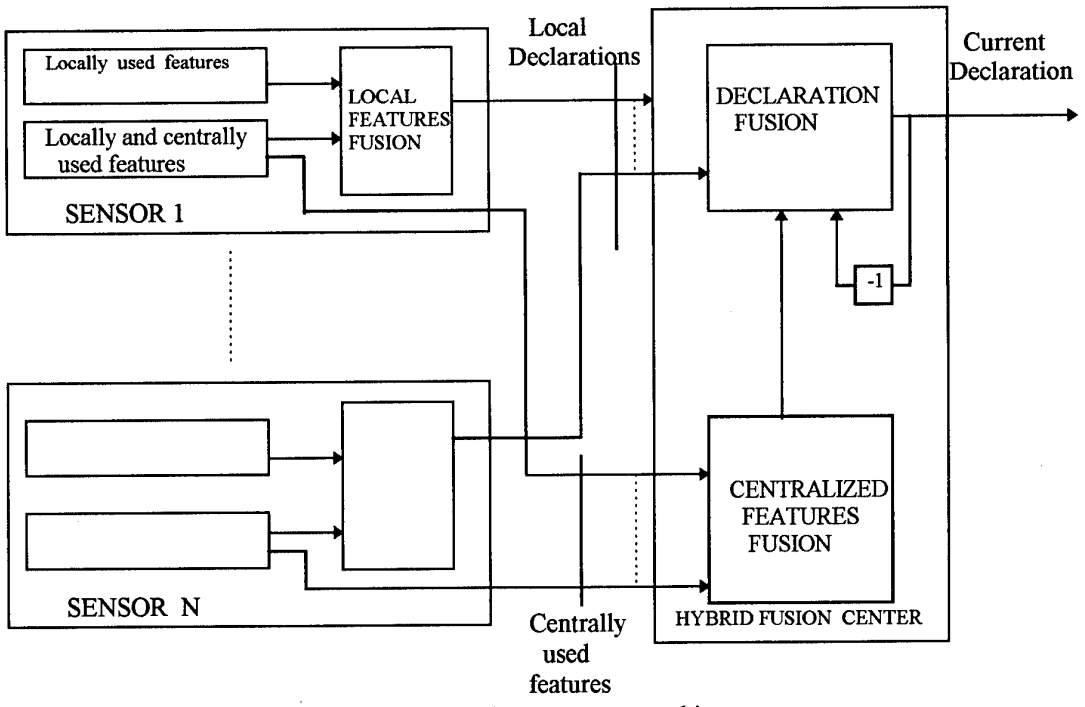


Figure 1 : Hybrid multisensor system architecture

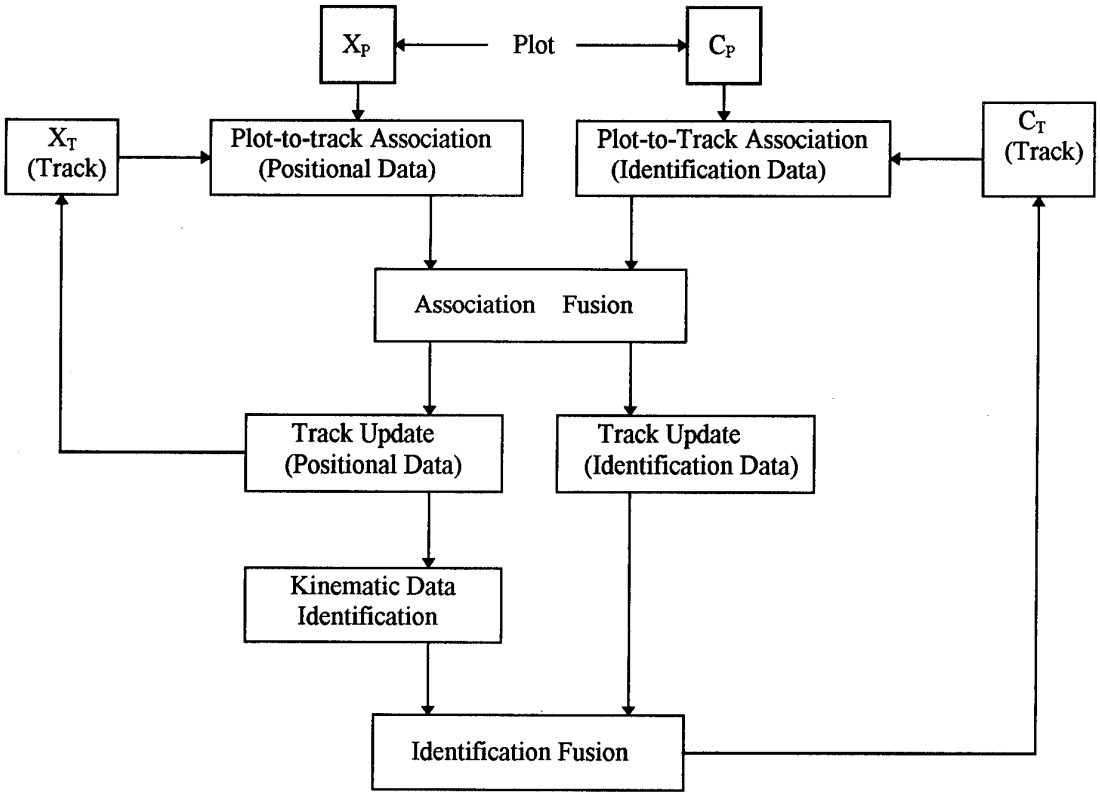


Figure 2 : Fusion algorithm diagram

		Declared Type			
		1	2	3	4
True Type	1	0.65	0.60	0.60	0.23
	2	0.04	0.94	0.01	0.01
	3	0.03	0.03	0.91	0.03
	4	0.16	0.11	0.05	0.68

Blade Flash Signal

		Declared Type			
		1	2	3	4
True Type	1	0.67	0.08	0.08	0.17
	2	0.32	0.53	0.04	0.11
	3	0.02	0.02	0.94	0.02
	4	0.24	0.40	0.24	0.12

Hub Signal

Figure 3 : Example Confusion Matrices

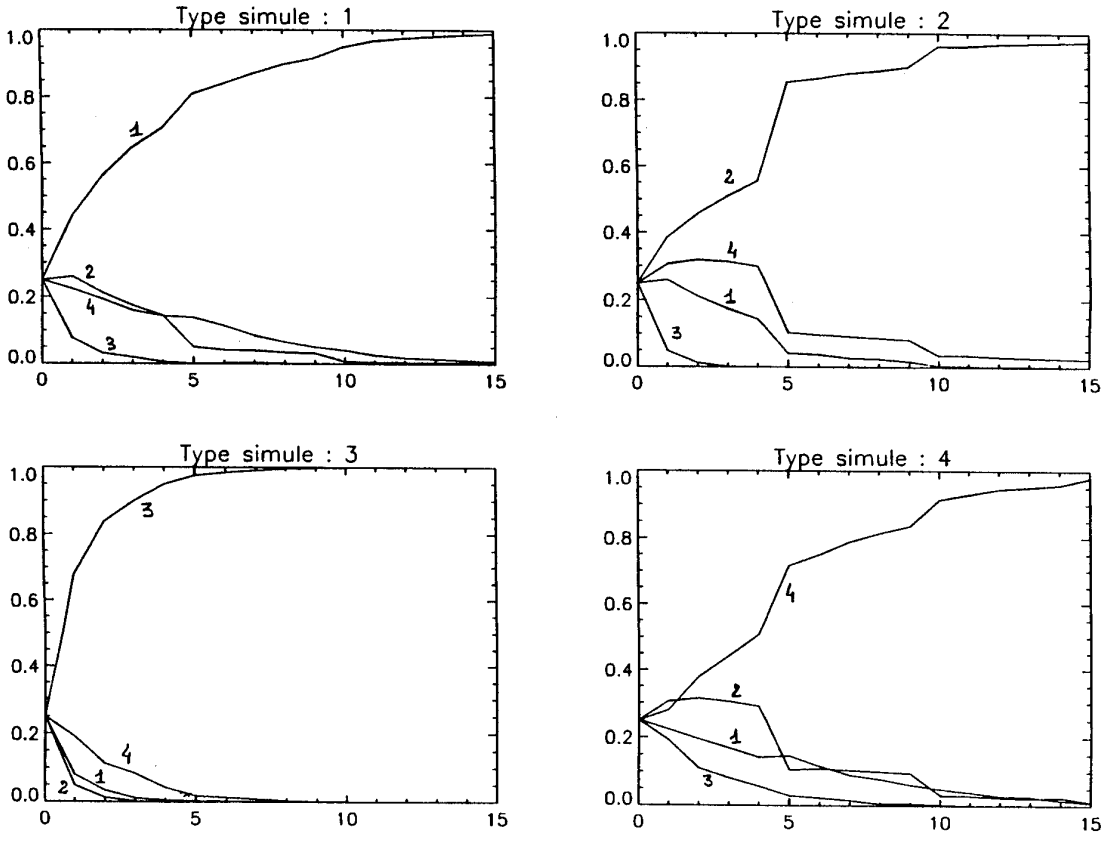


Figure 4 : Recursive classification using Bayes method

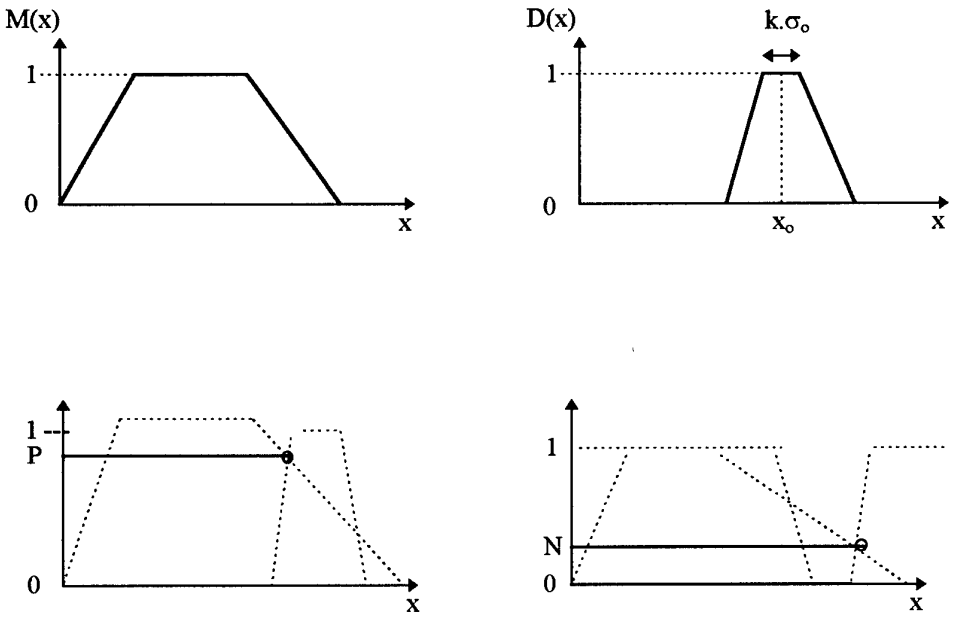


Figure 5 : Fuzzy logic basic principles

Distance based range profile classification techniques for aircraft recognition by radar - a comparison on real radar data

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ABSTRACT

Aircraft identification is essential in any air-defence scenario. Without a robust classification capability no effective threat evaluation can be performed. A prominent aircraft recognition technique is based on the exploitation of a one-dimensional image of a target, a *range profile*. In this paper, we employ four different classification techniques, all based on shift invariant distances, and a method to compare them. Two of the techniques are based on Radial Basis Functions for which a novel technique to optimize the number of free parameters is presented. The application is on real radar data, where a true separation between train- and test profiles is accomplished. The classification results are encouraging. As an example, a qualitative statement is given about the best of the four classifiers to be used in combinations of two scenarios and four applications.

1. INTRODUCTION

An important aircraft identification technique, Identification Friend Foe, relies on the cooperation of the target. If, in war- or crisis time, the aircraft fails to cooperate for whatever reason the only *save* conclusion for the interrogator is that the aircraft is hostile.

This incomplete decision process caused serious cases of fratricide. In April 1994, two Blackhawk (friendly) helicopters were shot down in the no-fly zone of Iraq. This incident underlined again the importance of an additional identification capability such as NCTR (Non-Cooperative Target Recognition).

Currently we are investigating the NCTR potential of High Range Resolution (HRR) range profiles. Measurement of these signatures is relatively easy and the requirements for motion compensation are moderate or the compensation may even be omitted. Additionally, range profile classification is applicable at almost all aircraft orientations.

In the literature, several approaches to classify range profiles are reported. Selection of a feature vector from the spectral components of a range profile is reported by Garber *et al* [1], DeWitt [2] and Kouba [3]. Classification of this vector is carried out by a nearest neighbour rule, a *Hidden Markov Model* and a recurrent neural network, respectively. The latter two have the interesting ability to process *sequences* of range profiles. Baras and Wolk [4] showed the feasibility of range profile classification on multiple resolution levels using wavelets.

In real measurements, the absolute positions of the scatter returns in a range profile are undefined. It requires that the classification method should be shift-invariant. A promising solution to this problem is the use of correlation filters [5]. In this paper we investigate the potential of a shift invariant profile-to-profile distance. Once it is defined, all classification techniques that are based on these pair distances are available. Earlier results on such a distance metric using a nearest neighbour classifier (section 3.4) are reported by Novak [6].

Four different classification methods are devised and tested. Two of them are based on the Nearest Neighbour rule, the other two are implementations of a Radial Basis Functions network. In this study a thorough test on real radar data from inflight aircraft is carried out. An important property of the used data set is that the train- and test profiles were measured independently.

Furthermore, we present a method to compare the classifiers. Clearly, an important comparison criterion is the error on an independent test set. With an eye on future applications for a range profile classifier we believe that it is important to include the classification speed in the comparison as well. Two less important parameters are the time needed for training a classifier and the size of the classifier.

Finally, we select for all combinations of two scenarios and four applications the most appropriate classifier. Although these choices are rather tentative given the moderate amount of data that is considered, it clearly demonstrates the employed method.

The organisation of this paper is as follows: The next section reviews the physics of range profiles, section 3 describes the used distance metric and the four classification techniques. Then, section 4 establishes the approach to compare classification techniques. Section 5 shows the results on real radar data and, finally, section 6 gives the conclusions.

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2. RANGE PROFILES

Figure 1 shows the contour of an aircraft and its range profile. The profile can be viewed as a projection of the aircraft scatterers onto the line of sight. It thus shows the radar cross section as a function of range.

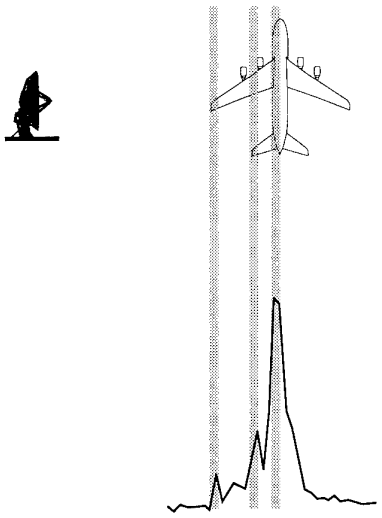


Fig. 1: The aircraft is illuminated from the left side. Each strip represents a range cell. The contributions of the scatterers in each strip are summed to constitute a single range profile element.

For the generation of range profiles, we need a radar that is able to emit a high bandwidth-waveform. This can be done either with a single short pulse, or with a burst of pulses at linearly increasing carrier frequencies [7].

Due to coherent summation of aircraft scatterers (speckle), the exact shape of the range profiles depends strongly on aspect angle. However, the overall profile shape does not change significantly (see for example figure 3) as long as the aircraft scatterers do not move outside one range resolution cell.

For the available data, the maximum change in aspect angle to avoid this *rotational range migration* is approximately 1.5 degrees. It is very difficult to determine the aircraft aspect angle with this accuracy. Consequently, a simple look-up table approach - a measured profile and its aspect angle is compared to the profiles in a data base with the same aspect angle - is not applicable [5].

Another approach is therefore to consider aspect angle bins that are several times larger than the *error* in aspect angle. The procedure is to construct a classifier for each bin. Then, for an unknown profile, retrieve its aspect angle, select the appropriate bin and assign a class with the corresponding classifier. Evidently, an extra mismatch probability will occur, because a profile from class 1 may look like a profile from class 2, as seen at a different aspect within the bin.

For the data set we consider in this paper the errors on the aspect angles are witnin five degrees. All profiles have aspect angles with absolute values ranging from 0 to 20 degrees and are placed in a single bin.

3. RANGE PROFILE CLASSIFICATION

3.1 Definitions

Two sets of independently measured range profiles within a single bin are available, the *input set* and the *test set*. A subset of the input set, the *train set*, is used for training a classifier. The profiles in the input set, train set and test set are randomly ordered and are named $\mathbf{r}_i$, $i = 1, \ldots, N_{\text{input}}$, $\mathbf{p}_i$, $i = 1, \ldots, N_{\text{train}}$, and $\mathbf{q}_i$, $i = 1, \ldots, N_{\text{test}}$ respectively.

A *classifier* is fully determined by

1. the *classification technique* and
2. the *train set*.

The classes of all profiles are known. This enables us to train and test a classifier. Clearly, in an operational situation there is no test set available.

3.2 Sliding Euclidean Distance

All our classification methods are based on profile-to-profile distances. The absolute positions of the reflections in the profile depend strongly on the distance to the target. As we cannot estimate this distance accurately enough to place the reflections on an objective position, we must use a shift invariant distance.

Suppose we have two range profiles $\mathbf{x}_1$ and $\mathbf{x}_2$, length α, elements $x(1), \ldots, x(\alpha)$. Then we define the distance D as the minimum Euclidean distance over all shifts:

$$D(\mathbf{x}_1, \mathbf{x}_2) \equiv \min_{j=0,\ldots,\alpha-1} \sqrt{\sum_{i=1}^{\alpha} \left[x_1(i+j) - x_2(i)\right]^2}$$

The shifts are cyclical, that is $x_1(\alpha + j) \equiv x_1(j)$.

3.3 Compression and normalisation of profiles

In profile classification using the Sliding Euclidean distance it is advantageous to lift the weak scatterers in the range profile relative to the strong scatterers so that they can play a role in the profile matching as well. Several choices can be made for such a *compression*, e.g. a log-scale or a power function with a power less than one.

Current investigations concern the search for the optimum compression function. Preliminary results show that a power function with a power ¼ works satisfactorily.

After the compression, the profiles need to be normalized, as the magnitudes of the reflections depend strongly on the absolute sensitivity of the radar and the distance at which the aircraft was measured. As neither the sensitivity nor the exact distance of the aircraft is known, we normalise the compressed profiles such that the sum of squares of the profile elements equals one.

3.4 Nearest Neighbour

The nearest neighbour rule decides that the class of a profile from the test set is the class of the nearest profile in the train set. Here 'nearest' is with respect to the chosen distance metric D.

A simple extension to this technique is to search for the k ($k \geq 2$) nearest neighbours, giving k class declarations. The class that occurred most frequently is assigned to the profile

from the test set. Experiments showed that this extension did not give significant differences in the classification results. Therefore we will only consider a 1-nearest neighbour in this paper.

3.5 Condensed Nearest Neighbour

A drawback of the nearest neighbour technique is the large computational effort necessary for the classification. For each profile for which classification is desired, we have to compute all distances to the profiles in the train set again. This is even more a problem in our application, because the chosen distance measure D is computationally expensive.

The technique we will apply here to reduce the computational burden is based on the idea that a profile that is far from the decision boundary has, on average, far less influence on the outcome of the nearest neighbour classifier than a profile that is near the decision boundary. Therefore we might as well skip this profile and save the computation time.

It is possible that a profile does not contribute to the decision boundary at all, as it is completely surrounded by other profiles from the same class. Skipping it does not alter the outcome of a nearest neighbour rule. However, in our application this situation seldom occurs as a profile is of very high dimension and thus almost always defines a part of the decision boundary. This means that in virtually all cases the classification accuracy is reduced if a profile is removed.

In this paper, we use the *condensing* algorithm [8]. To arrive at the condensed subset of the train set, two complementary subsets of this set, named A and B, are defined. Place the first profile from the train set, $\mathbf{p}_1$, in A, the remaining profiles, $\mathbf{p}_2$, . . . , $\mathbf{p}_{N_{\text{train}}}$, in B. The method proceeds as follows:

1. Use the nearest neighbour rule to classify the first profile in B with the profile(s) in A. If it is classified correctly with the nearest neighbour rule, leave it in B, otherwise, place it in A. Repeat this operation for all profiles that are left in B.
2. If in step 1 not a single profile has been transferred from B to A, or if B is empty then terminate. Else return to step 1.

After termination, A contains the condensed subset. For classification, the nearest neighbour rule is applied using the condensed subset instead of the full train set.

3.6 Radial Basis Functions

Radial Basis Functions (RBF) provide a way to construct a function that maps vectors from a high dimensional space onto a lower dimensional space [9]. As the only inputs for this method are distances between profiles we can use the sliding Euclidean distance D to make the method suitable for range profile classification. The advantage of the used RBF implementations compared to a nearest neighbour technique is the large reduction of classifier size and classification effort.

From the train set, L profiles are selected to serve as *centres* $\mathbf{c}_l$, $l = 1, \ldots, L$. (The next two subsections 3.7 and 3.8 describe the used selection methods.) The pair distances between the centres and a train profile $\mathbf{p}_i$ enter the RBF network and form the elements of a distance vector $\mathbf{d}_i$ with elements:

$$d_{il} = D(\mathbf{p}_i, \mathbf{c}_l) \tag{1}$$

Then, a non-linear transform using a Gaussian function

$$\phi(r) = e^{-\frac{r^2}{2}} \tag{2}$$

is applied to each of the elements in the distance vector, giving

$$b_{il} = \phi(d_{il}). \tag{3}$$

Multiplication of the vector $\mathbf{b}_i = (b_{i1}, \ldots, b_{iL})^T$ by a weight matrix W and addition of a bias vector $\mathbf{w}_0$ gives, for each train profile, the output $\mathbf{o}_i$.

$$\mathbf{o}_i = \mathbf{w}_0 + W\mathbf{b}_i \tag{4}$$

In the training phase, the weights $\mathbf{w}_0$ and W are chosen such that the outputs are as close as possible to unit vectors in a γ-dimensional space, where γ is the number of classes.

Train profiles from class 1 are mapped as close as possible onto the output $\mathbf{e}_1 \equiv (1, 0, \ldots, 0)^T$, train profiles from class 2 onto $\mathbf{e}_2 = (0, 1, \ldots, 0)^T$, et cetera.

Hence the training of the Radial Basis Functions network boils down to finding the least squares solution for $\mathbf{w}_0$ and W using equation 4 for all train profiles. This is an attractive property of the Radial Basis Functions approach: although it is able to construct any complex non-linear decision boundary, the weights can be found by linear methods [9].

For classification we simply compute the output for a *test* profile $\mathbf{q}_i$ using the distances D to the centres and equations 3 and 4. If the closest unit vector to the output is $\mathbf{e}_j$ then class j is assigned to the test profile.

In the next sections we will address the problems of choosing the centres and selecting the number of centres.

3.7 Radial Basis Functions with Random Centre Selection

A good first choice for the centres is to select them randomly from the train profiles. One must be careful, however, about the number of centres to choose. Each extra centre adds an extra degree of freedom to fit the train profiles. If we take too few centres, the approximation will be too coarse. If we take too many centres (but less than the number of train profiles), also the noise on the profiles will be fitted ('overfitting'). In both cases, the generalisation capabilities of the classifier will be worse than with an intermediate number of centres.

To find the optimum number of centres we devised the following algorithm:

1. Select, randomly, half of the profiles from the train set, and use them as *evaluation* set. Use the other half as *design* set.
2. Choose, randomly, a profile from the design set (one that has not been chosen earlier) and copy it to the *centre* set.
3. Find the weights using the centre set and the design set from equation 4.
4. Compute the outputs $\mathbf{o}_i$ for each of the evaluation profiles. Compute the sum of the errors $\| \mathbf{o}_i - \mathbf{e}_j \|$ where $\mathbf{e}_j$ are the desired outputs corresponding to the class of the evaluation profiles. This is called the *evaluation error*.
5. Repeat steps 2, 3 and 4 until all design profiles (apart from one) are used as centre.

Similarly to step 4 it is instructive to compute the *design error* as well.
Although this error decreases monotonically as the number of centres increases, the evaluation error will reach a minimum for a certain number of centres. See figure 2. The best choice for the number of centres is therefore at the minimum value of the evaluation error.

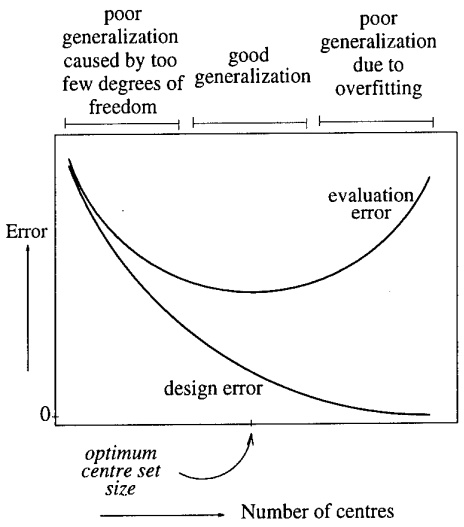


Fig. 2: As the number of centres increases the network is able to represent the design profiles better, i.e. the design error tends to zero. However, the true classification capability is revealed by the error on an independent evaluation set.

3.8 Radial Basis Functions with Gram-Schmidt Centre Selection

A procedure to select the best centres from the design set is to use a Gram-Schmidt orthonormalization technique. Here we will confine ourselves to a qualitative description, for details we refer to [10].
As in the Random Centre Selection, the first step is to employ the first part of the train set for designing the classifier and the other part for evaluation. Then we search for *that* profile in the design set that gives the best least-squares solution if used as a centre. At each next step, we add another profile to the centre set that gives the best improvement of the least-squares solution.
Instead of the computation of the least-squares solutions, Chen *et al* [10] devised an efficient Gram-Schmidt orthonormalization procedure to select the best centres.
As in the random centre selection, we compute the classification error on the independent evaluation set and choose that number of centres where the evaluation error has a minimum.

4. COMPARISON OF CLASSIFIERS

Often, classification techniques are compared in terms of their errors on a test set only. For most practical applications three more properties define the usefulness of a classifier. The following list gives the four measurable classifier properties that are of interest.

a_1 Classification error [% false on independent test set]
a_2 Computational effort needed for one classification [# floating point operations]
a_3 Computational effort needed for training the classifier [# floating point operations]
a_4 Memory required to store the trained classifier [# of bytes].

Ideally, each of these quantities equals zero. In practice, for each classification technique there will be a trade-off between these four properties which can be found by varying the size of the train set.
For example, let us consider a classifier that uses the nearest neighbour technique ($a_3 \equiv 0$) and a small sized train set. Then the classification error, a_1, will decrease if the train set increases. This also implies, however, that more distances have to be computed and it thus results in a larger a_2 and a_4.
To choose the right classifier we would like to have weight functions, ω_i (monotonously increasing) so that the quantity

$$\sum_{i=1}^{4} \omega_i(a_i) \tag{5}$$

is minimized with respect to $a_1, \ldots, a_4$. Unfortunately, we do not have these functions available, but we can make a few simplifying but realistic assumptions to tackle the problem.
The first one is that the most important parameters in a military context are a_1 and a_2. The time needed for training (a_3) is of much lesser importance, because it can be done off-line. The size of the trained classifier is generally also less significant. Besides that a_4 is (almost) linearly related to a_2 for the classification techniques we consider. Therefore we do not have to minimize a_4 by itself. For the remainder of this paper, we will therefore focus on a_1 and a_2 only.
We do not make a choice for ω_1 and ω_2 either, but construct a large number of classifiers to demonstrate the trade-off between a_1 and a_2. For example, if the user wishes a certain a_1 he may find in a single curve the classifier that has the smallest a_2.
At this point, we also want to stress that not only the application (e.g. surveillance or aircraft radar) is decisive for the classifier choice, but also the scenario (crisis or wartime). As an illustration table 1 shows roughly the importance of correct classification and fast classification as a function of the application and the scenario.

This table shows in qualitative terms that in times of crisis it is more important to have a reliable answer then to have a quick answer. In wartime it is of greatest important to have a fast answer.

5. RESULTS

5.1 Available data

We have an input set available of 357 profiles of four different aircraft from an S-Band radar. The number of elements of the profiles is 128. These profiles were gained in six different aircraft flights.

	scenario	crisis		wartime	
	classifier property	correct class.	fast class.	correct class.	fast class.
application	SHORAD	+	0	0	+
	HIMAD	+	−	0	0
	Fighter aircraft	+	0	0	+
	Surveillance	+	−	0	−

Table 1: Relative importance of classification properties for application and scenario in terms of minus signs (less importance), zeroes (moderate importance) and plus signs (high importance). Here SHORAD means SHOrt Range Air Defense and HIMAD HIgh to Medium Air Defense (e.g. HAWK, PATRIOT).

In five other measurements, 339 profiles were obtained from the same four aircraft. These profiles made up an independent test set.

For each profile, an approximate aspect angle is available. The absolute aspect angles (we assume symmetry around aspect angle 0) are in the range of 0 to 20 degrees from head-on. The errors on the angles are believed to be within 5 degrees, the elevation is approximately zero.

As stated in subsection 3.3 the profiles were compressed with a power of 1/4 and normalised. Figure 3 shows some examples of compressed and normalised profiles from the four different classes and from the input- and test set. Each of the three profiles in one class and one set was measured during the same flight. This means that, although the aspect angle is inaccurate, the change in aspect angle (as indicated above each profile) is more accurately defined.

5.2 Classification experiment

In this section we investigate the properties of the classification techniques of chapter 3. To this end, we construct a large number of classifiers using the four techniques and varying train sets to monitor the trade-offs between the classification speed and the classification error.

Carry out the following steps for $N_{\text{train}} = 8, 24, 40, \ldots, 152$:

1. Choose, randomly, $N_{\text{train}}/4$ profiles per class from the input set and use them as train set.
2. Construct the classifiers
   - **NN** (Nearest Neighbour)
   - **CNN** (Condensed Nearest Neighbour)
   - **RR** (Radial Basis Functions with Random Centre Selection)
   - **RGS** (Radial Basis Functions with Gram-Schmidt orthonormalization)

   for this train set.
3. Classify all profiles in the test set using these classifiers. Compute the percentage of false classifications. This gives a_1. Also keep track of the number of flops used for classifying a single profile (a_2).
4. Repeat steps 1-3 thirty times and average a_1 and a_2.

The results are shown in figures 4 and 5.

Figure 4 shows that a fairly good classification rate can be achieved with only a small number of profiles per class in the train set. For example the nearest neighbour technique needs only 40 train profiles (on average one profile per class per two degrees) to achieve a classification error less than 11%. It suggests that a rather crude coverage of aspect angle suffices for reasonable classification, although one must be aware that the performance is favoured by the small number of classes. For all sizes of the train set, the nearest neighbour technique has the best classification rate. This technique apparently makes the best use of the available data. For small sizes of the train set, both Radial Basis Function techniques have poor classification rates. This is because half of the profiles has to be used for evaluation. If the train set increases, this effect becomes less important.

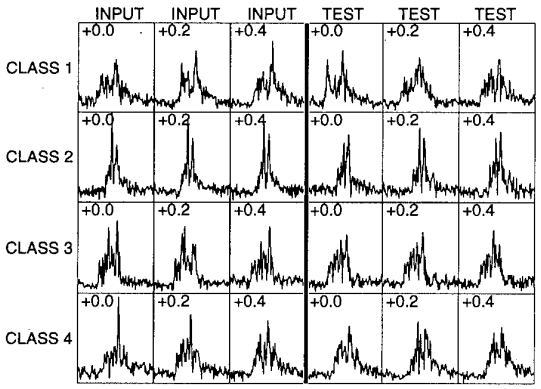


Fig. 3: Examples of compressed and normalised profiles of four different aircraft, near head-on. The input set is shown on the left hand side and the independent test set on the right hand side. In the upperleft corner, the aspect angle difference (in degrees) relative to the leftmost of the three profiles is shown. As can be seen, the small scale variations (speckle) are unpredictable whereas the overall appearance, in most cases, is similar.

The condensed nearest neighbour has an approximately 6% higher classification error rate than the normal nearest neighbour for all sizes of the train set. As stated in section 3.5, the condensing procedure deletes profiles that somehow contribute to the decision boundaries.

The Radial Basis Functions using a Gram-Schmidt centre selection has a somewhat better classification rate than the RBF using a random centre selection. For larger input sets, the difference tends to vanish.

The classification effort (figure 5) is closely related to the number of profiles that is present in the classifier.

In the nearest neighbour case, all profiles are used in the classifier - the CNN classifiers use the condensed profiles only. The classification effort is exactly linearly related to the

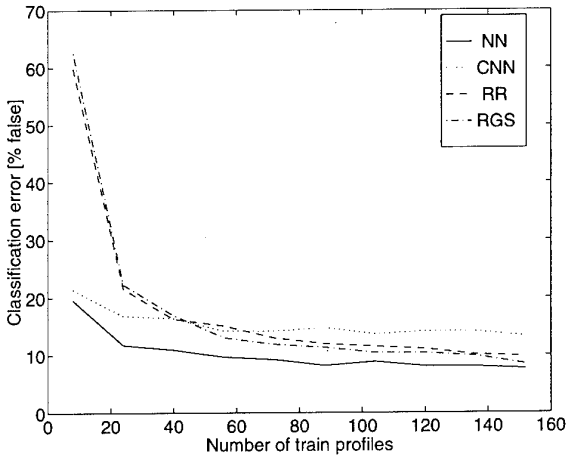


Fig. 4: Average percentage wrong (a_1) as a function of train set size.

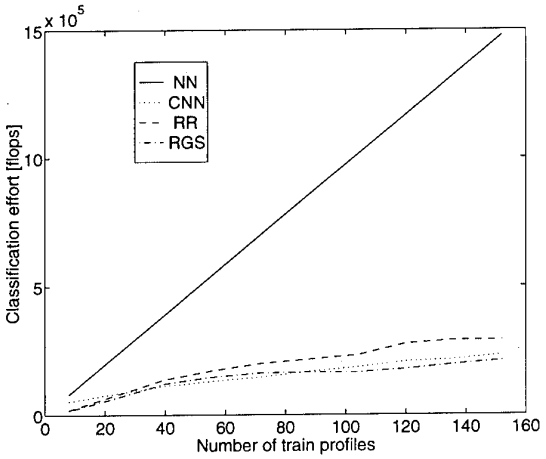


Fig. 5: Average classification effort for resulting classifier (a_2) as a function of train set size.

number of profiles in the train set (NN) or the number of condensed profiles (CNN).

The left-over profiles in an RBF classifier are the centres. The major part of the computations arises from the profile-to-profile distance evaluations - a small number of extra computations is necessary for the non-linear transform (equation 2) and the matrix multiplication (equation 4).

The two plots show that in the CNN-, RR- and the RGS classifiers only a very small number of profiles is left over, compared to the nearest neighbour. It means that redundant or nearly redundant profiles are removed at the cost of an increased classification error.

As the important parameters are a_1 and a_2, figure 6 shows the trade-offs between classification rate and classification speed for the four classification techniques.

From this figure one can decide which classifier is most appropriate for a particular classification purpose. The simple approach is to choose a desired classification error on the vertical axis, move horizontally until the first curve in the plot is reached. This classifier should be used as it is the most rapid one. For example, if one desires a classification between approximately 9% and 14% an RGS classifier is the best choice. The required size of the train set can be found in figures 4 or 5.

Conversely, figure 6 can be utilised to find the best classifier given a desired classification speed. E.g. if one is willing to carry out 10,000 flops for one classification, a CNN classifier is the best choice, because it has the minimum error of approximately 17%.

If one desires the minimum classification error possible, a nearest neighbour is appropriate, but it will take a long time to answer.

Returning to the table 1 we may insert, using figure 6, the most appropriate classification techniques; see table 2. We want to stress that filling in this table is merely a demonstration of the method of classifier selection - for a decisive answer on which techniques to use, larger scaled experiments have to be carried out.

6 CONCLUSIONS

In this paper we described a successful classification test on range profiles. The profiles used for training and those for testing were acquired in strictly separated aircraft flights and covered a wide aspect angle range of 20°. Still, the best classification results were within 10% error. Although these results are favoured by the small number of classes, they are very encouraging for the applicability of this technique for NCTR.

All classification techniques we considered were based on profile-to-profile distances. The best rates were found using a simple nearest-neighbour rule. In this paper we demonstrated, however, that for most cases this is not the best technique if one includes the classification speed into the comparison as well. It shows that the Condensed Nearest Neighbour and the Radial Basis Functions with Gram-Schmidt orthonormalization have a more favourable trade-off between classification rate and -speed.

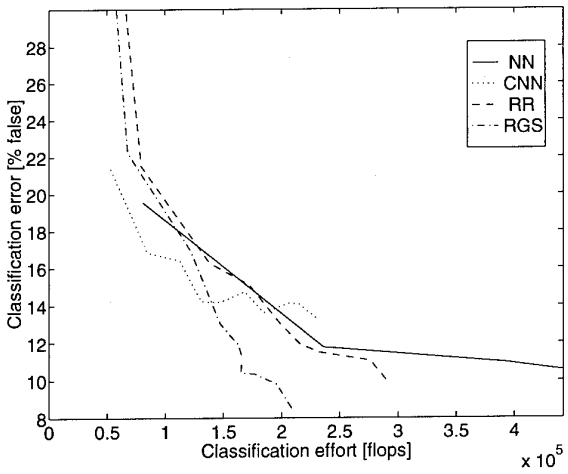


Fig. 6: Average classification effort (a_2) vs Average classification rate (a_1) (zoomed).

	scenario	crisis	wartime
application	SHORAD	RGS medium train set	CNN small train set
	HIMAD	RGS large train set	CNN small train set
	Fighter aircraft	RGS medium train set	CNN small train set
	Surveillance	RGS large train set	CNN medium train set

Table 2: Best classification technique given scenario and application.

7. ACKNOWLEDGEMENT

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MISSION PLANNING AND TASKING

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After having summarized the Mission Planning evolution during the last two decades this paper introduces the Mission Planning family of systems concept and presents an example : the CIRCE 2001 family in service with the French Air Force. In conclusion the to day's trends are briefly analyzed.

1. Mission Planning history

Schematically one can identify three steps in technology.

- First generation systems (before 1985)

Due to limited performance these equipment brought only a partial automation of the tasks to be achieved manually by the crew. the main improvement was related to performance computation and data transfer cartridge loading. One can say that coming out of cartridge has made such systems necessary.

We notice than, despite a digitizing table, the paper maps handling remains a time consuming task for the pilot.

- Second generation systems (1985 - 1990)

These systems are fully digitized thanks to emerging technologies such as map digitization, graphic processors, optical disks, and, very soon, the use of graphic workstations providing simultaneously computing power and graphic power.

The first system without any paper maps is the PALOMA system created in 1986 by SAGEM to plan the Mirage 2000N missions -including the ASMP planning- then extended to the Super Etendard fitted with the same missile in the naval aviation. More than 300 maps were assemblied in an optical disk along with the relevant terrain elevation model. This system is made of a computer and a graphic processor since graphic workstation were not available.

The systems based on work stations appear approximately two years later, the AFA in Germany dedicated to the Tornado, the MSS II in the US having the F16 and F111 capability.

In these systems the mission planning process is completely digital. Nevertheless they are mainly dedicated to a given aircraft and lack growth capability.

- Third generation systems (from 1990)

The tremendously increasing performances of computers, graphic engines, storage media added to software open architecture made it possible to give systems multiship capability. Such evolution has been seen simultaneously in France and in the States where the MSS III program initially aimed to the Tactical Air Command aircraft has been enlarged to become finally the AFMSS (Air Force Mission Support System) taking into account all of the USAF aircraft.

In addition to this extension, horizontal in some way, another extension, a vertical one became also possible thanks to the flexibility of hardware and software. This is the multi level concept which allows for tailoring same family systems from Force Level Systems to Unit Level portable systems through Squadron Level systems.

2. The CIRCE 2001 family

During the last two years this concept has been validated through the delivery to the French Air Force of three types of systems belonging to the CIRCE 2001 family.

- SPP/PM : Mission Planning and Tasking System, at Force Level

- SLPM 2000D : Local Mission Planning System, at Squadron Level

- SLPM ATT : Dedicated to Hercules and Transall, this system include a portable equipment for every aircraft.

Such a family can be identified by its common patrimony as well as by the links between its members.

- The CIRCE 2001 patrimony

All CIRCE 2001 systems share the following patrimony :

. Compatible and modular hardware
. Same Software open architecture
. Standard Man Machine Interface
. Functions library
. Common data bases
. Homogeneous Security policy

- The CIRCE 2001 links

All systems belonging to this family are linked together by X25 long distance networks and locally through Ethernet.

Obviously they also can be linked to other systems especially at Force Level.

After this analysis of the CIRCE 2001 family we will now describe each system features.

3. The family systems

The three systems are presented from the unit level to the force level system.

- Portable CIRCE

The main feature of this system is its small scale in terms of weight and volume, this does not imply a proportionnal performance reduction. The major cuts are applied to the peripherals capabilities and the screen size.

In addition the data storage is limited as well as the number of available net work interfaces.

This systems having been designed mainly for military aircraft plans the two missions of such aircraft -logistic

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and tactic- and takes into account specific requirement such as cargo optimisation.

Finally the system loads the disk which transfers the data into the Flight Management System and prints a flight log.

- SLPM 2000D

To be easily carried in a C130 or a C160 the SLPM 2000D is made of ruggedized containers. Two versions have been delivered either single or dual operated systems. In the latest one, each operator is provided with its own workstation, some peripherals being shared by two operators.

The system is fitted with significant peripherals such as the juke box in which is implemented a huge geographical data base. It is linked to equivalent systems through local networks inside an Air Force Base and connected to the Force level system and the portable system through long distance networks.

The SLPM 200D is not a dedicated system but a multi ship one. It takes into account, for each type of aircraft, sensors and weapons as well as tactics and navigation modes.

When the mission planning is completed, a color Combat Mission Folder is printed and the data cartridges are loaded.

- Le SPP/PM

Compared to local systems the SPP/PM hardware features are the computing power the network interface capability and also it is a multioperator system ; so far at the request of the French Air Force three operators an working simultaneously.

The SPP/PM software is made of the addition of all existing local planning functions and specific tasking functions. Therefore it has all the squadron level capability including Combat Mission Folder edition and Data transfer Cartridge loading. But its main feature consists in mission tasking which includes :

a) target analysis,

b) Plan definition through each mission basic points (take off, target, landing) and plan parameters,

c) global optimization of trajectors taking into account,
- aircraft data (consumption, weapons, navigation)
- geographical data
- tactical situation

d) Chronology,

e) Deconfliction : conflicts identification and automated deconfliction.

4. Current trends

Some trends are currently identified that could be taken into account for future systems design as well as for existing systems improvment.

At the squadron level the link between postflight debrief (damage assessment and tactical situation update) and mission planning is yet clearly identified. The emerging Part Task Trainers could also be linked to the squadron level mission planning systems and even share hardware components such as CPU, software functions such as 3D rehearsal, tactical and geographical data.

At the Force Level it should be under lined that the system capabilities described previously (plan definition, global optimization, chronology, deconfliction) are very close to an automated Air Tasking order generator. Therefore it would make sense to integrate the Air Tasking Order generation and despatching into the mission tasking and planning system in stead of having a separate aso dedicated system.

Decision Tool for optimal deployment of radar systems

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1. SUMMARY

A Decision Tool for air defence is presented. This Decision Tool, when provided with information about the radar, the environment, and the expected class of targets, informs the radar operator about detection probabilities. This assists the radar operator to select the optimum radar parameters. In the future, a Decision Tool will be developed that advises the radar operator about the optimum selection of radar parameters.

2. INTRODUCTION

In many cases, a radar operator has more than one radar system at his disposal in order to search for approaching targets. These systems may differ largely with respect to transmitted power, antenna gain, frequency, polarization, noise figure and signal processing. Further, for each radar system, the operator can choose some parameters like pulse repetition frequency, pulse length, frame time, etc. Which radar system and which set of parameters will yield the largest possibility of detection depends heavily on the actual propagation conditions (ducting!), on the target that is expected (altitude, velocity), and on the clutter from the environment.

TNO-FEL has developed a computer program called PARADE that, provided with a set of radar parameters and actual meteorological conditions, calculates radar coverage diagrams as a function of range and altitude. The program can also compute detection probabilities as a function of range and altitude for a given target radar cross section and velocity. It is based on the program described in [1]. Some examples will be shown, displaying the capabilities of PARADE. PARADE is currently being extended to a Decision Tool, which can advise the operator which radar system to use and which parameters to select.

3. DECISION TOOL

As has been pointed out in the introduction, the performance of a radar system depends not only on the set of parameters chosen by the radar operator, but also on the environmental conditions and on the class of targets that is expected.

Among the environmental conditions that influence the radar performance are multipath and ducting. Multipath is the well-known phenomenon that the radar signals travelling from the radar to the target follow several paths: the direct path, and one or more paths via the ground or via obstacles (Fig. 1). Arriving at the target, these signals interfere with each other, resulting in either increased or decreased total signal strength. Whether ducting occurs depends on the way the index of refraction n of the atmosphere changes with altitude h. This in turn depends on the temperature profile, the relative humidity and the wind speed. Whether ducting occurs can be determined easily from the dependence of the modified refractivity M with altitude. The modified refractivity is defined as

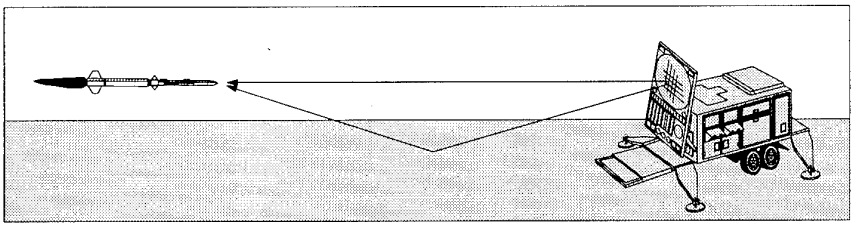


Fig. 1: Multipath.

$$M(h) = (n - 1 + h/a)\times 10^6 ,$$

where a is the radius of the earth. When there is a layer in the atmosphere in which M decreases with increasing altitude, ducting occurs, and part of the radar signal is trapped in the duct. Four types of duct are illustrated in figure 3.

Apart from trapping, superrefraction, subrefraction or standard propagation may occur (Fig. 2), depending on the exact meteorological conditions that determine the refractivity profile.

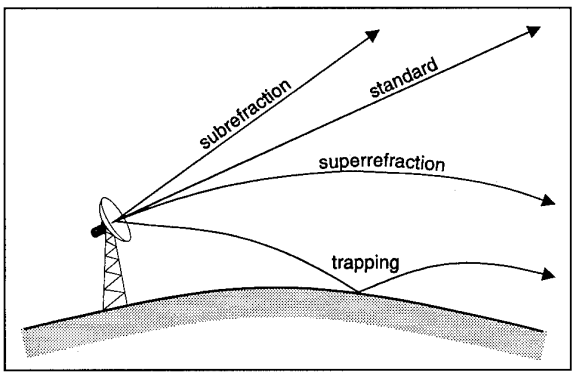
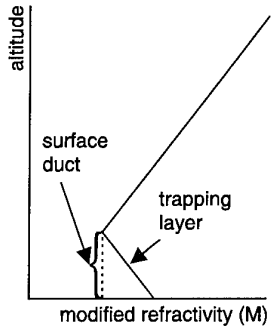
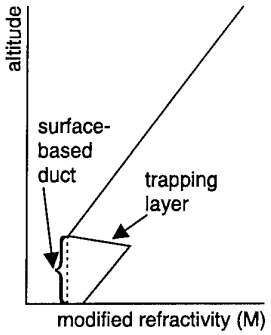


Fig. 2: Wave paths for various refractivity conditions.

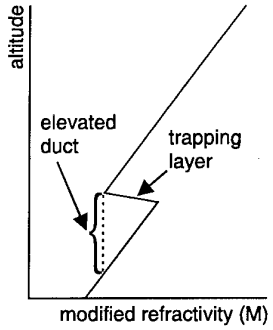
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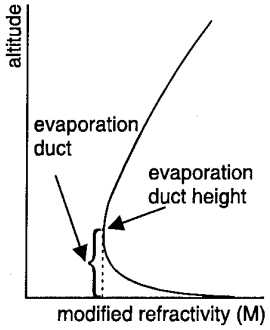
a. Surface duct formed by a surface trapping layer.



b. Surface-based duct formed by an elevated trapping layer.



c. Elevated duct formed by an elevated trapping layer.



d. Evaporation duct formed by a decrease of humidity immediately adjacent to the sea surface.

Fig. 3: Examples of atmospheric ducts.

The combination of multipath and duct may give rise to very complicated propagation paths. In figure 4 a so-called "coverage diagram" is presented for an evaporation duct height of 20 m. The radar frequency is 16 GHz and the antenna is located at an altitude of 8 m and has an elevation of zero degrees. Note that the path loss is very large at altitudes of 3 to 4 m for all ranges except the very short distances. This means that a low flying missile can approach the platform without being detected when a frequency of 16 GHz has been chosen for surveillance under these circumstances. Obviously, when the radar operator has a Decision Tool available that informs him about the actual radar coverage, he will not stick to this frequency. More information about propagation can be obtained from [2,3,4].

Apart from the transmitter frequency of the radar, there are other radar parameters that have a significant influence on the detection probabilities. The pulse repetition frequency (PRF) of the radar introduces so-called blind ranges and blind velocities [5], as is illustrated in the "blind zone diagram" of figure 5.

Blind ranges occur because, at the moments the radar is transmitting a pulse, the reception of echoes from previous pulses is not possible. The time between two pulses is 1/PRF, in which PRF is the pulse repetition frequency, which is often in the order of kHz or tens of kHz. Therefore, for targets at distances that are integer multiples of $c/(2\times PRF)$, in which c is the speed of light, the possibility of detection is zero. In figure 5, the PRF is 5 kHz, and hence the blind ranges occur every 30 km.

Blind speeds occur because the clutter spectrum, which has a peak at a Doppler frequency of zero, repeats itself with a period equal to the pulse repetition frequency. As a consequence, when the Doppler frequency shift of a target is an integer multiple of the PRF, the target return has to compete with the ground clutter. Hence, when the target velocity is an integer multiple of $\lambda\times PRF/2$, in which λ is the wavelength, the possibility of detection is reduced. In figure 5, the wavelength is 0.03 m, and hence the first blind velocity occurs for a target velocity of 75 m/s.

In order to optimize the possibility of detection for a certain class of targets, it is obviously important to choose the PRF with care, or to vary the PRF regularly. The regular variation of the PRF is called staggering. The Decision Tool can assist the radar operator to make the right selection.

Apart from multipath, ducting, blind ranges, blind velocities, and clutter, also hostile jammers often pose a problem to the radar operator. The Decision Tool is able to predict the reduced detection probabilities in certain angular sectors when a jammer is present. This is illustrated in figure 6, where a scenario with three jammers has been chosen.

4. FUTURE DEVELOPMENTS

In the previous section, we have discussed a Decision Tool that informs the radar operator about detection probabilities,

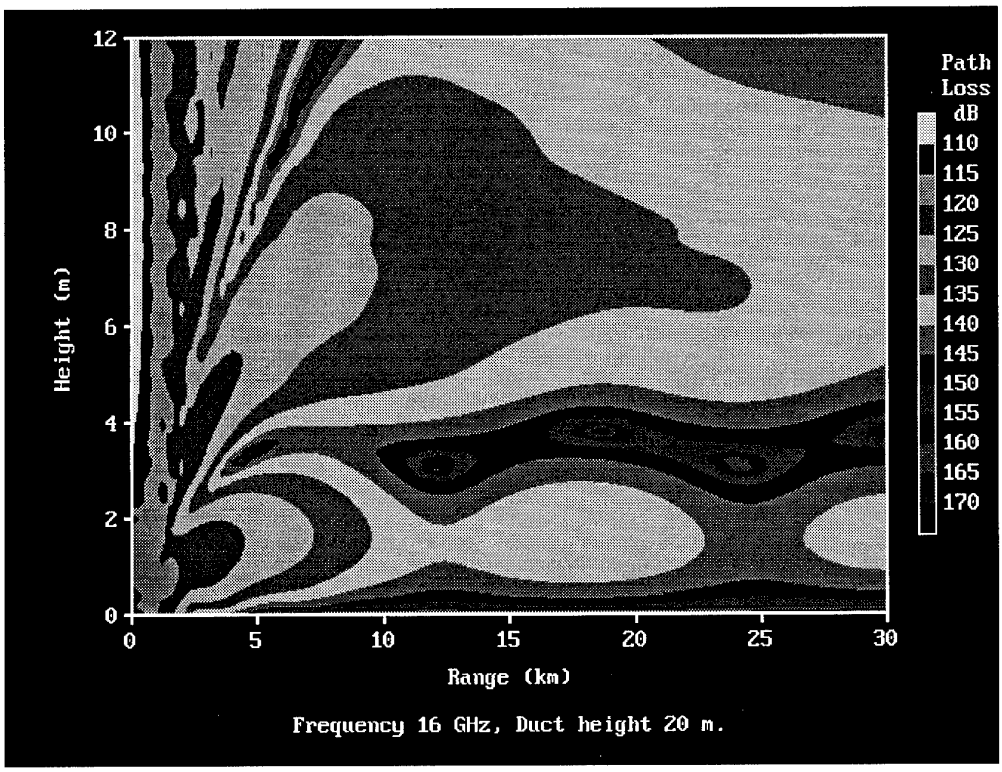


Fig. 4: Coverage diagram. Evaporation duct height 20 m, transmitter frequency 16 Ghz.

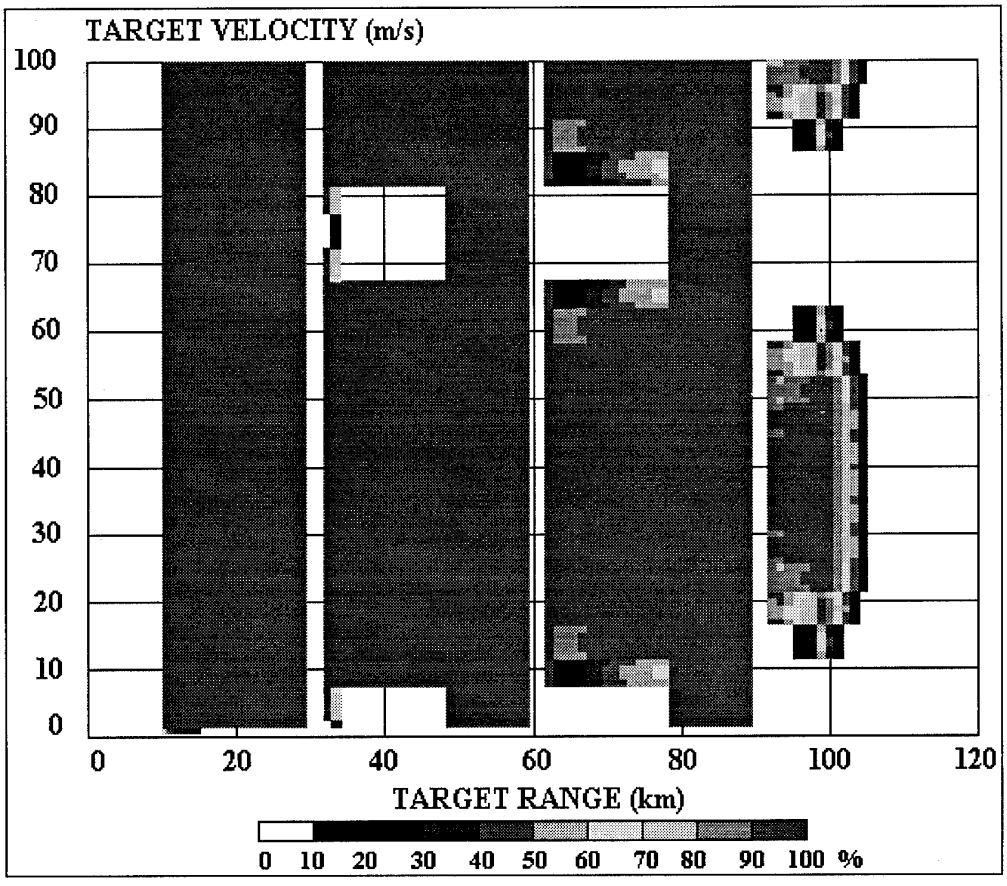


Fig. 5: Blind zone diagram. PRF = 5 kHz.

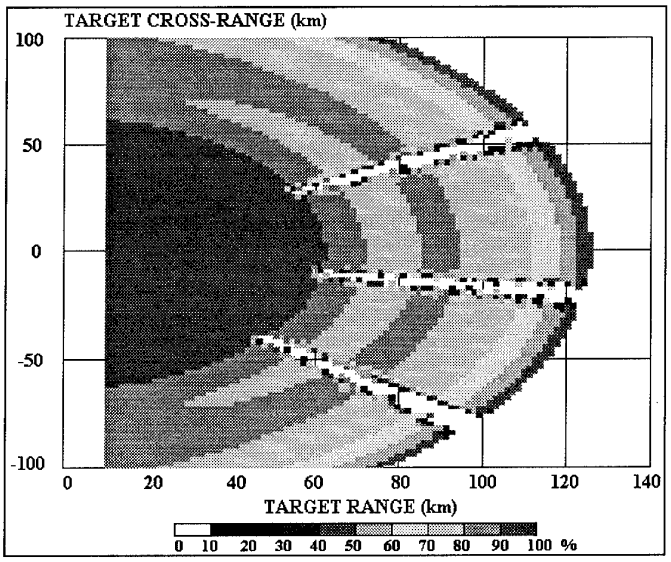


Fig. 6: Horizontal coverage diagram for a scenario with three jammers.

based on the selected radar parameters, the environmental conditions, the presence of jammers and the class of targets expected. When the operator wants to obtain the optimum radar parameters, he has to try out many possibilities. Often, he does not have the time for this. Therefore, we intend to modify the Decision Tool, in such a way that it is capable to advise the operator about which parameters to select, or, when applicable, to advise how to stagger several parameter values. As the Decision Tool is computationally intensive, parallel processing will be needed.

Further, it is our intention to increase the applicability of the Decision Tool. For instance, we wish to incorporate a more advanced propagation model in order to be able to calculate propagation over rough seas and over terrain with hills, cliffs and buildings. A possible model for this is given in [6]. Of course, in this case we will also need a more sophisticated clutter model to calculate the clutter returns from terrain. Another application for which we will need a more sophisticated clutter model is high-resolution radar. When radar pulses are very short, the clutter becomes very spiky, so that, for a certain average clutter level, false alarms can occur more often.

Last but not least, we wish to incorporate models for infrared systems in the Decision Tool, as infrared systems and radars can be complementary. An operational range prediction model for infrared search and track systems is presented in [7]. When the radar has a reduced coverage in a certain sector, because of the propagation conditions, the background clutter or jammers, the Decision Tool may advise to rely more on an infrared system in this sector. On the other hand, when the infrared system has a reduced coverage in a certain sector because of background radiation or aerosols, the Decision Tool can advise to rely more on the radar in this sector. For an optimum use of the time budget of the search systems, the Decision Tool can allocate certain sectors of the search volume to the radar and other sectors to the infrared system.

5. CONCLUSION

We have presented a Decision Tool that assists radar operators to select the optimum radar parameters for air defence, given the radar systems available, the environmental conditions and the class of targets that is expected. Some future developments have been discussed. The Decision Tool is expected to be a very powerful aid for both radar operators and commanders, and is expected to increase platform survivability.

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Adaptive Strike Planning With Search Path Allocation

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1. SUMMARY

Adaptive strike missiles have the capability to autonomously find and attack targets. In many cases, the location of the target is not known, and the missile must perform a search of the region in order to detect any existing targets. This search entails the planning of a search flight path, tailored to the sensor's capabilities, that will maximize the probability of detection.

The Search Planner is composed of a search path subsystem that includes: 1) a tactical motion analyzer that takes into account terrain and feature data, and determines a probable search region based on the motion capability of the target; 2) a feature extractor subsystem which generates most-likelihood feature maps, such as tree-lines, that govern possible target locations within the critical region; 3) a path generator subsystem that determines the best search path by first covering the possible target locations with rectangular strips and then chaining them together in a near-optimal way; and 4) a sensor manager that optimizes allocation of sensor resources as the missile travels through the search region.

To validate our concept, we have integrated the Search Planner into a many-on-many simulator that functions to optimally allocate a missile strike force *en-route*. This paper describes the design of the Search Path Planner subsystem which consists of a Search Area Generator, a Segment Generator, a Link Generator, and a Link Chainer module.

2. APPROACH AND RESULTS

The following figures (1 through 16) illustrate the overall concept, its sub-systems, the algorithms, and results of a simple example.

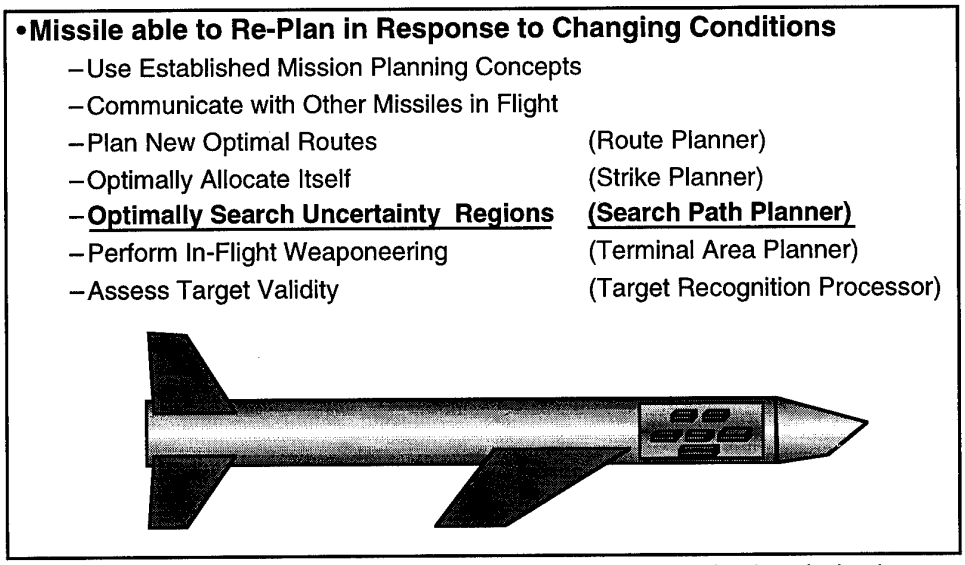


Figure 1. The concept is for an autonomous missile to be able to re-plan its mission in response to changing conditions in the environment. This system must be able to (1) Communicate with other missiles such that each individual missile has knowledge of how it fits into the mission; (2) Plan new optimal routes; (3) Optimally allocate itself to a target within the battle scenario; (4) Assess the validity of a given target via Automatic Target Recognition.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

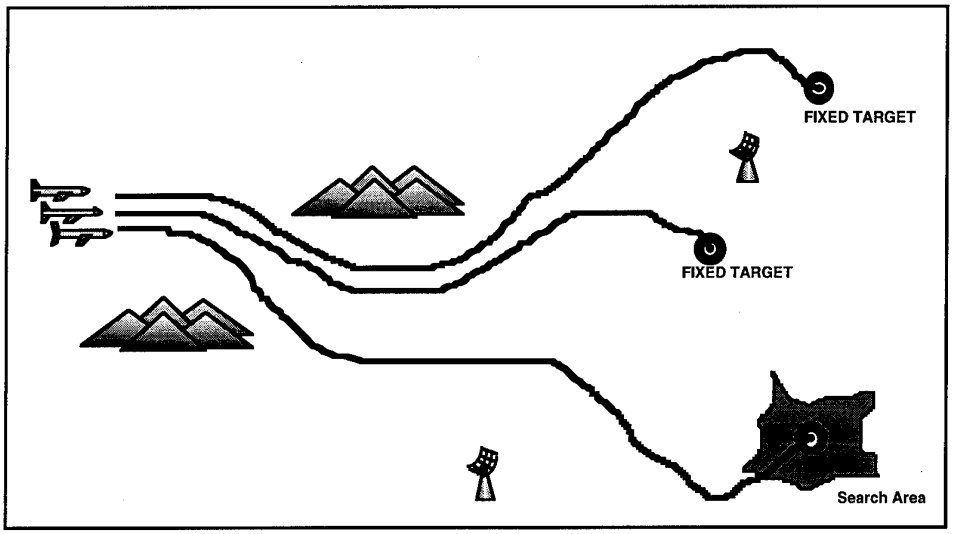


Figure 2. Missiles are used to attack both fixed targets and area targets. There are two types of area targets: (1) Mobile targets that have moved from known positions as originally determined by reconnaissance; 2) Targets in uncertainty regions where the presence of targets is unknown.

Search Path Planner: Requirements

- **Area Search:**
  - **Search Arbitrarily Shaped Areas for Targets**
  - **Optimize Search If Given**
    - » **Feature Data**
    - » **Rules-of-Thumb**
      - **Likely Areas**
      - **Direction of Search**
- **Relocatable Targets:**
  - **Search Area for Specific Target**
  - **Optimize Search If Given**
    - » **TMA Information**
    - » **Feature Data**
    - » **Rules-of-Thumb**
      - **Likely Areas**
      - **Direction of Search**

Figure 3. (1) Area Search occurs when we plan to search an arbitrarily shaped area for targets, and the targets have not been localized. (2) Re-locatable target Search occurs when a localized target is capable of movement while the weapon is en-route. The Tactical Movement Analyzer developed at Jet Propulsion Laboratory (JPL) is used to estimate the outer bound of the area, as a function of time, that will contain the mobile target.

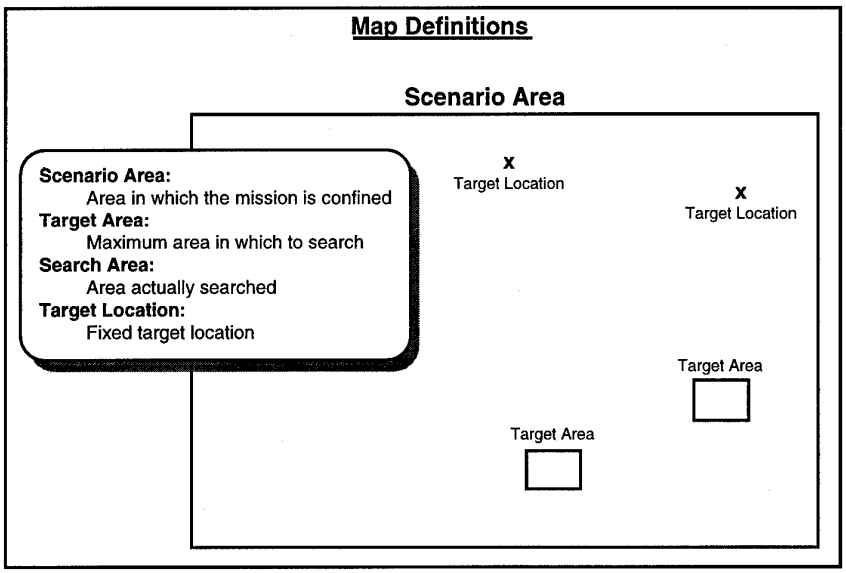


Figure 4: The *Scenario Area* is the area in which the whole mission will be contained. The weapons will never fly outside of the scenario area. The *Target Area* is the maximum area that will be searched. If we have information as to the terrain and the mobile target movement capabilities, we can use this information to reduce the size of Target Area to a smaller region called the *Search Area*. The *Search Area* is the area that the missile will actually search. The *Target Locations* are simply the locations of fixed targets.

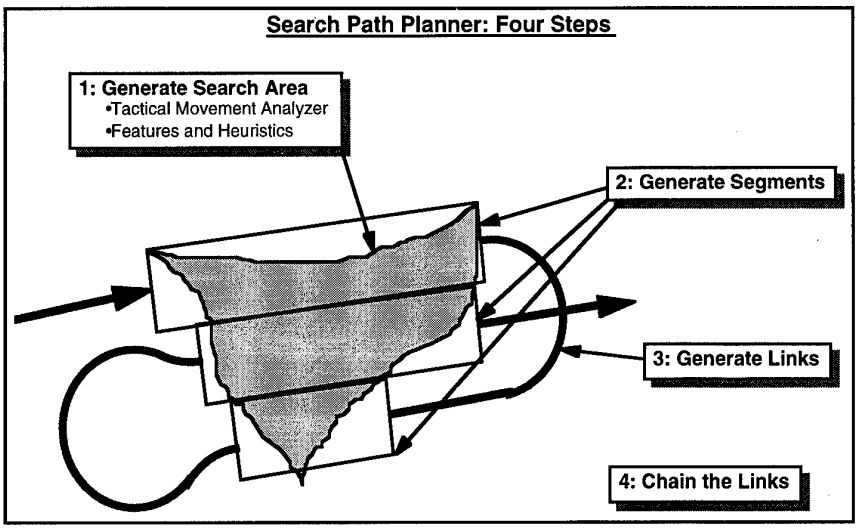


Figure 5: The first step is to define the search area. If there is information available that can narrow the search to more likely areas (within the target area) we will exploit this information. Such information includes the vehicle's ability to traverse terrain, and the elapsed time since the target was last sighted. We can further reduce the search area by exploring high probability features such as roads, tree lines, railways, etc., and de-emphasizing low priority features such as lakes, swamps, and mountainsides. The second step is to generate the search segments. These are the search swaths used to cover the search area. The third step is to generate the segment links. These are the flight paths from the exit points of one search segment to the entrance points of the next search segment. The fourth step is to chain the segments and select the optimal or near-optimal chain.

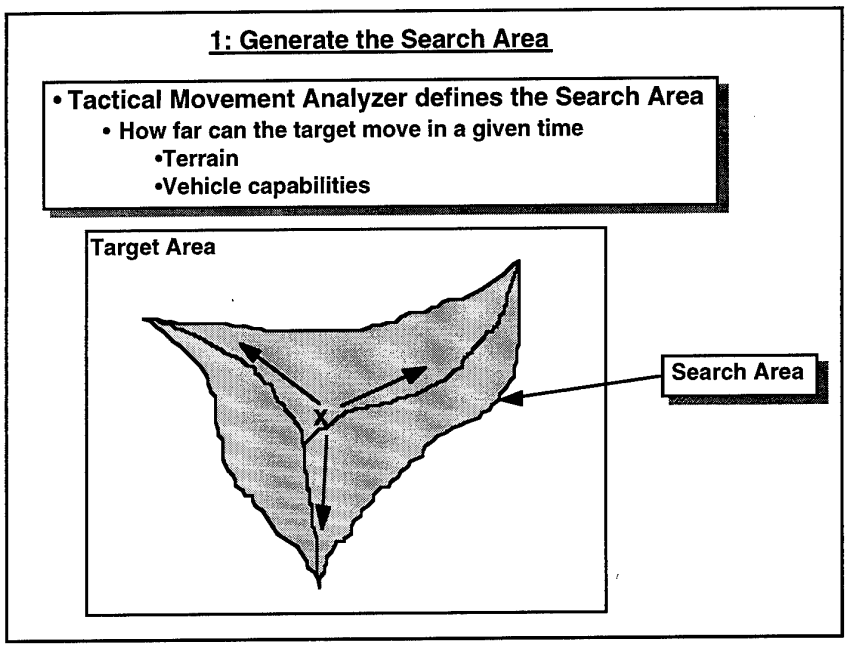


Figure 6: A system called the Tactical Movement Analyzer (TMA) developed by Jet Propulsion Laboratories is used to generate the search area. The Tactical Movement Analyzer estimates the area that would contain the target after a fixed amount of time. It takes into account the type of terrain, features, weather and the vehicle's ability to traverse that terrain. The output from the TMA is a set of points which is input to the Search Area Segmenter.

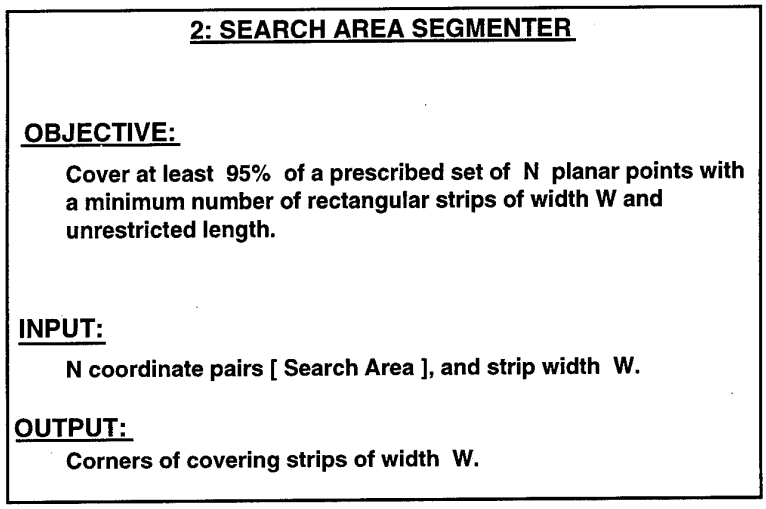


Figure 7: The objective of the Search Area Segmenter is to obtain a minimum number of rectangular strips of width W and unrestricted length. These rectangular strips will cover at least 95% of a prescribed set of points which represent the probable locations of targets. This value, 95%, is a user selected parameter and is used to adjust for the significant effect the last few percent can have on the total flight distance. The input to this subsystem is a binary (1,0) grid map of the search area, where the 1's represent search points and the 0's represent non-interest points. The search width is also specified and is a function of the missile flight altitude and the seeker field-of-view. The output of this subsystem is a set of four-corners of the covering strips.

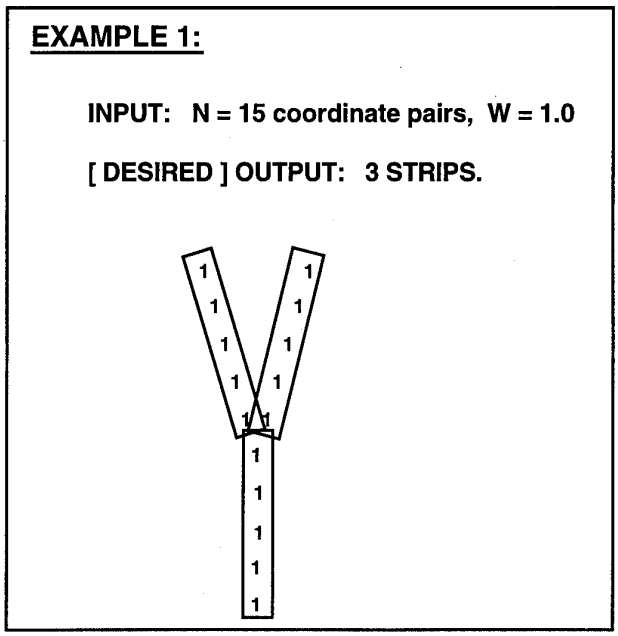


Figure 8: An example of the function of this Search Area Segmenter is as follows. The probable target locations are indicated by the 1's in the figure. The desired output of the Search Area Segmenter is three rectangular strips that cover the three limbs.

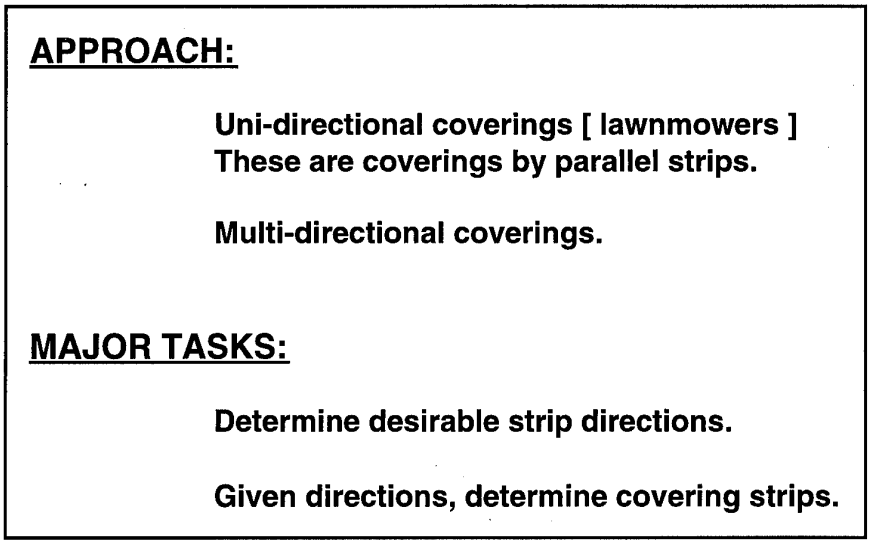


Figure 9: For the Search Area Segmenter, the approach we have taken is to divide the problem into two categories. If the search area can be covered by a number of parallel strips, then we will use a "lawnmower" coverage. Otherwise, we will use a multi-directional covering scheme where the strips are generally non-parallel. The tasks are to determine the desirable strip directions, and given these directions, determine the covering strips.

	DETERMINE DIRECTIONS	DETERMINE STRIPS
UNI-DIRECTIONAL	hull facets	linear K-cover
MULTI-DIRECTIONAL	boundary histogram	best-first heuristic

Figure 10: For the first case of "lawnmower" coverage, the desirable direction is determined by the dominant direction of the convex hull facets. The Graham Scan algorithm is used to determine the convex hull and the "caliper" algorithm is used to obtain a rectangular directional hull. Determination of strips which are placed over a directional hull is then reduced to a linear K-cover problem. If a multi-directional coverage is desired, we use a boundary histogramming approach to iteratively obtain the segment directions. The strips are then determined by a best-first, or, "greedy" algorithm.

FUNDAMENTAL FACT:

For a fixed direction, covering planar points by strips reduces to covering linear points by intervals.

This reduces the 2-dimensional problem to the line.

RESULTING METHOD:

For fixed direction DIR, project the Search Area onto the line normal to DIR. Now cover the linear point set with intervals.

Figure 11: In the "lawnmower" coverage mode (fixed direction), covering planar points by strips reduces to covering linear points by intervals. This reduces the 2-dimensional problem to a 1-dimensional problem. An example of the technique follows.

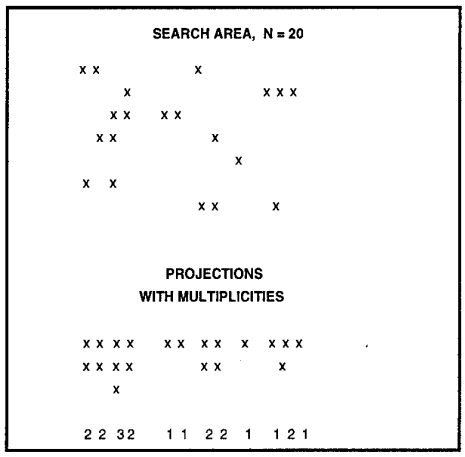


Figure 12: The 20 crosses (x) in the upper portion of the figure are to be covered by vertical strips in the "lawnmower" scheme. The orthogonal or perpendicular direction to the strip direction is therefore "horizontal". This technique reduces the 2-dimensional problem to a 1-dimensional problem, and is performed by projecting all the crosses (x) to a horizontal line (orthogonal or perpendicular) to the direction of the strips which are vertical in this example. These multiplicity numbers on the horizontal line represent the number of crosses covered by a vertical strip at that position. For instance, 80% of the crosses are covered by 4 vertical strips of width 2.

3: GENERATION OF LINKS BETWEEN SEGMENTS

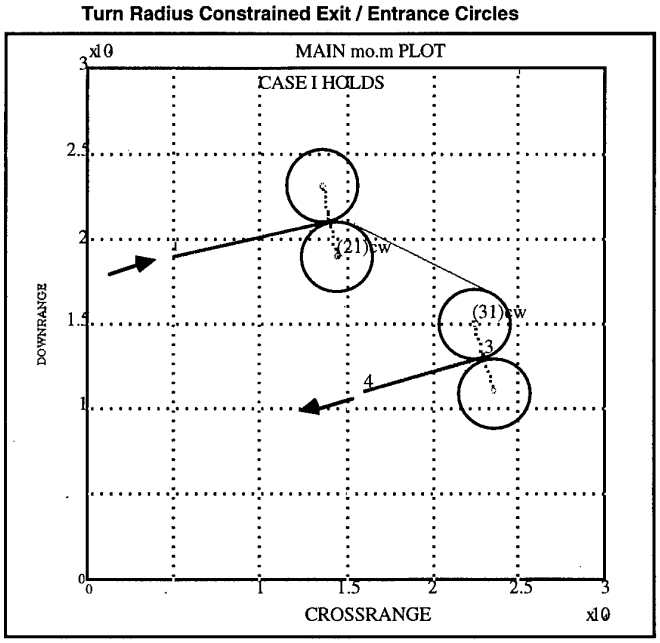


Figure 13: Once the rectangular segments are determined, their coordinates are sent to the Segment Linker function which generates flight paths between segments. The flight dynamics of the platform are accommodated by including the turn radius as an input to the process of generating the set of all possible links between search segments. In the example, two segments are shown and we wish to exit the top segment from its right side and enter the lower segment from its right side too. The maximum "g" turn radius circles are shown at the exit and entrance points.

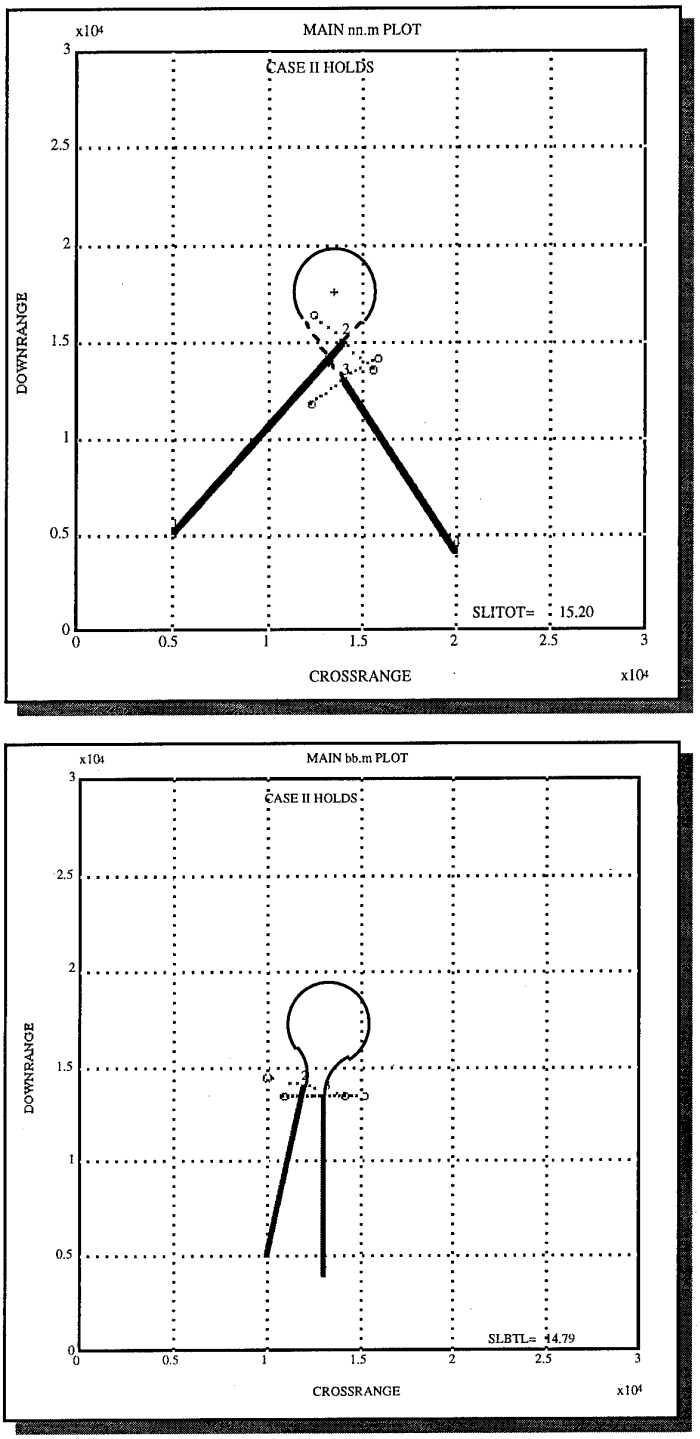


Figure 14: Shown here are examples of two flight paths that might be used to join segment ends that are closer than two turn circle radii. Simple geometric algorithms and logic discriminates are applied to determine the flight path between segments within the Segment Linker function.

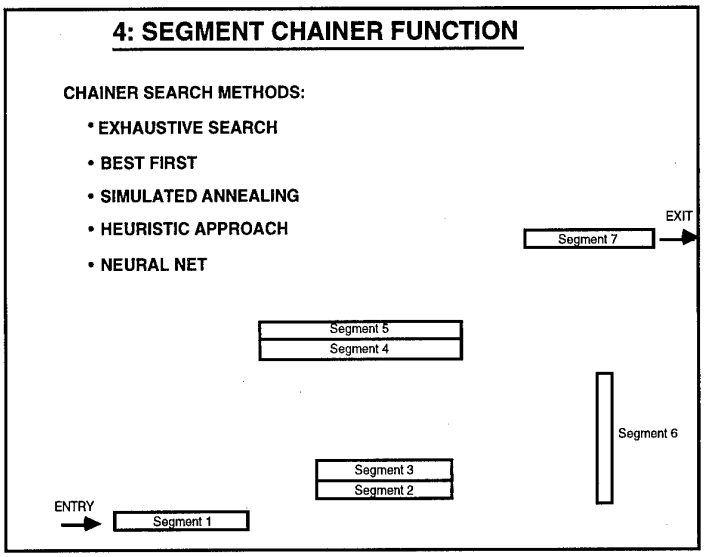
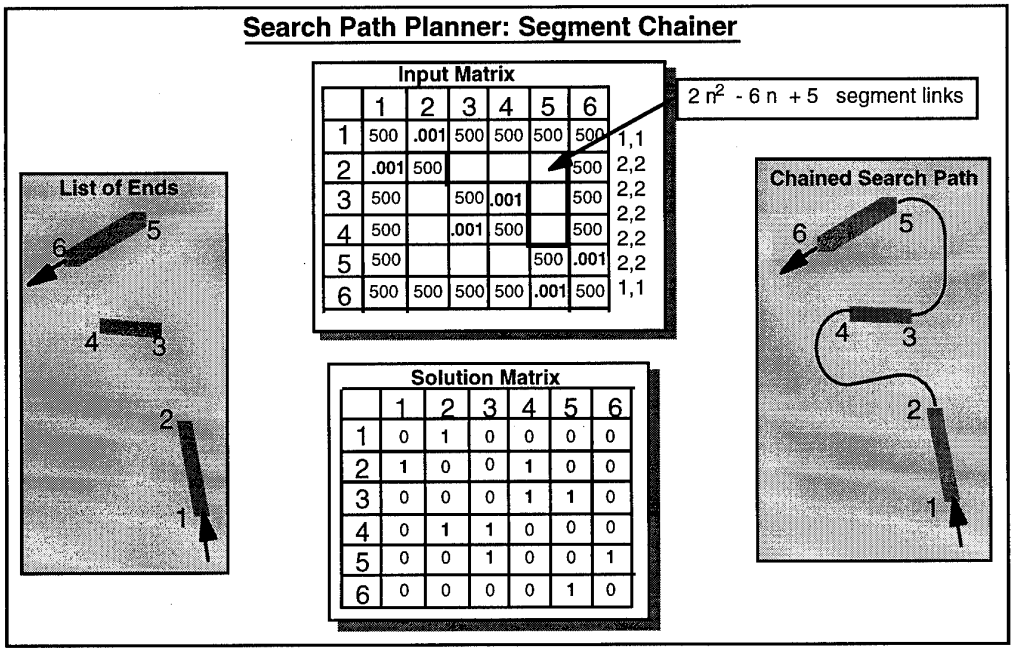


Figure 15: Once we have calculated the set of all segment links, we must chain them together into a single, near-optimal, flight path. The idea is to chose a method or combination of methods that will give a solution to this "assignment" problem in a timely manner. In addition, system memory constraints must be taken into account. In this example, there are seven segments which implies that there are 3840 possible flight paths between the exit point of segment one and the exit point of segment seven. One path is desired and is determined by the Segment Chainer.



	1	2	3	4	5	6	
1	500	.001	500	500	500	500	1,1
2	.001	500				500	2,2
3	500		500	.001		500	2,2
4	500		.001	500		500	2,2
5	500				500	.001	2,2
6	500	500	500	500	.001	500	1,1

	1	2	3	4	5	6
1	0	1	0	0	0	0
2	1	0	0	1	0	0
3	0	0	0	1	1	0
4	0	1	1	0	0	0
5	0	0	1	0	0	1
6	0	0	0	0	1	0

Figure 16: Jet Propulsion Laboratory (JPL) has provided us with a neural net solution which allows for adjustable, multiple, assignments based on system constraints. Using this approach, we construct a cost matrix according to our constraints, and input this matrix to the neural net. This neural net then generates the solution matrix. This solution matrix provides our assignments, which links our segments to form a near-optimal or optimal pathway.

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4. ACKNOWLEDGMENT

Mr. Kevin Sheldon edited the manuscript.

"Approved for public release; distribution is unlimited."

C3I, Simulation technico-opérationnelle et Wargame

Une démarche pour un atelier de production de C3I orienté Simulation

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1. Le problème

1.1 Les décisions et les coûts

Le déroulement d'un programme de quelque importance pose un problème majeur lié à sa durée : pour des raisons d'homogénéité et de facilité de contrôle, les décisions majeures en termes d'architecture sont prises très en amont. L'avantage est que le coût du programme est assez vite fixé (en termes de coût prévisionnel), l'inconvénient est que le coût du programme est imprévisible (en termes de coût réel).

En effet d'une part le besoin à l'origine du programme évolue (choix entre résultat inutile et révision déchirante), d'autre part le progrès technologique est à prendre en compte (choix entre résultat obsolète et refonte architecturale).

L'intérêt du responsable de programme est de prendre le plus tard possible les décisions de conception, ou au moins de les étaler au maximum. Nous montrerons que la simulation est en ce sens une aide puissante.

1.2 De quelle simulation parlons-nous ?

En gros, simuler, c'est substituer à un système un autre plus simple capable de mimer son comportement externe avec un niveau de détail et un niveau de vraisemblance donnés.

Cette définition naïve fournit un axe de classification (un seul, car finesse et vraisemblance sont très liées). On simplifiera encore en ne retenant que trois points :

- **Simulation technico-opérationnelle** : niveau grossier, vraisemblance limitée aux généralités fonctionnelles. Les modèles sont simples et ne permettent généralement pas une représentation fidèle (interaction humaine exclue), mais exécutables rapidement : on peut simuler un grand nombre d'acteurs, de nombreuses fois (Monte Carlo). Non temps-réel, ce niveau est adapté aux études paramétriques à grande échelle (concepts, doctrine, validation de besoin).

- **Jeu de guerre** : niveau juste assez fin pour rendre possible l'interaction humaine, au moins par moments. Les modèles étant plus complexes, le nombre d'acteurs possibles est restreint. Éventuellement temps réel, ce niveau est celui de l'étude et de la validation tactiques.

- **Simulateur** : C'est le niveau de détail maximum. Sa complexité le limite à un système unique, l'environnement pouvant être simulé ou non. L'interface entre le système simulé et le monde réel (opérateurs inclus) est reproduite dans ses moindres détails.

Nous laissons volontairement de côté les simulateurs d'entraînement qui se situent quelque part entre les deux derniers niveaux mais sont hors de notre propos.

1.3 La place de l'opérateur humain

Selon le niveau étudié, l'opérateur humain va être pris en compte soit de manière virtuelle sous forme d'un modèle simple, voire simpliste (simulation technico-opérationnelle), soit en devenant un acteur dont les actions auront une incidence plus ou moins prépondérante sur le déroulement de la simulation (jeu de guerre ou simulateur). La définition du modèle pour intégration à la simulation technico-opérationnelle suppose de caractériser des comportements attendus proches de ceux observés dans des situations analogues.

La présence de l'homme dans la boucle de fonctionnement des jeux de guerre et encore plus des simulateurs apporte un élément primordial par son interaction en temps réel sur les processus de fonctionnement du système. Elle impose par contre de répondre de manière adéquate aux contraintes inhérentes à

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la présence humaine. Ces contraintes peuvent se classer en quatre grandes catégories :

- contraintes d'ordre sensori-moteur, en fonction de l'organisation physique du poste d'activité : il est souvent nécessaire de concevoir des postes côte à côte, avec écrans couleur et IHM reconfigurables, afin de faciliter la réalisation de tâches concertées et de minimiser les risques d'erreurs,

- contraintes de type neurophysiologique liées à la durée et à l'organisation des services ainsi qu'à la monotonie ou à la surcharge de travail pour certaines périodes d'activité : le recours à des tâches transférables est alors à envisager,

- contraintes de nature cognitive, au niveau de la représentation mentale que les opérateurs se feront du système, et plus particulièrement du fonctionnement des automates : des aides et des assistances sont à prévoir et à évaluer sur simulateur afin d'appréhender les délais nécessaires à une prise de décision lors de situations complexes et critiques,

- contraintes de formation et d'entraînement des personnels concernés.

D'une manière générale les tâches incombant à l'opérateur humain peuvent concerner :

- la surveillance courante de la situation,

- l'optimisation de la visualisation de cette situation,

- la supervision du fonctionnement de processus automatiques,

- l'intervention en cas de doute sur le fonctionnement,

- le recueil de renseignements et d'informations caractérisant un événement,

- le besoin d'anticiper en fonction de l'évolution de la situation,

- la gestion des moyens de communication,

- le contrôle de l'état des équipements,

- la compensation d'automatismes en cas de panne,

- l'optimisation de l'utilisation des différents équipements.

Cet ensemble de tâches implique de :

- privilégier le principe d'un affichage minimal des informations selon le contexte du moment,

- préserver la compréhension par l'opérateur humain de l'état de fonctionnement pendant les phases de faible activité (surveillance),

- offrir des possibilités d'anticipation avant et en cours de situations critiques.

2. Simulation d'un C3I

Nous nous intéressons ici aux fonctions principales impliquées par l'acronyme :

- Commandement et contrôle,
- Communication,
- Renseignement.

2.1 Système à logiciel prépondérant

Un C3I est avant tout une machine à acquérir, filtrer, présenter et diffuser l'information. Son comportement est entièrement décrit par du logiciel. L'aspect matériel, bien que non marginal (C3I embarqués en particulier, dispositifs de communication en général), n'est pas prépondérant dans la recherche de satisfaction du besoin.

On peut répartir grossièrement les services logiciels selon les fonctions :

- Commandement et contrôle : filtrage contextuel, présentation et aide à la décision, cartographie.

- Communication : gestion de réseau, filtrage sécuritaire, cryptage.

- Renseignement : traitements divers (imagerie), fusion, présentation, cartographie.

Cette répartition n'est pas exhaustive.

Simuler un C3I, c'est en fait réaliser un logiciel plus simple que le logiciel du système réel. Rien n'interdit à une simulation bien construite d'évoluer peu à peu vers un logiciel opérationnel. Le mot clé est *bien construit*.

2.2 Système d'aide à la décision et facteur humain

Le point clé à résoudre consiste à faciliter la compréhension de la situation en apportant des informations cohérentes en regard de la représentation mentale de l'opérateur.

La difficulté réside bien souvent dans le fait que l'homme et le système n'ont pas les mêmes attributions ni les mêmes modalités de fonctionnement.

Les tâches dites fermées, c'est-à-dire dont les objectifs restent identiques à chaque réalisation de la tâche, sont confiées au système; pour chaque réalisation, les paramètres demeurent en général peu fluctuants et prédictibles.

Les tâches dites ouvertes, dont le mode opératoire est propre à chaque réalisation de la tâche, incombent par contre à l'homme. Il doit donc décider du cheminement satisfaisant en fonction du contexte du moment, avec une assistance éventuelle par un ou des automates plus ou moins évolués, sur lesquels il pourra agir en termes d'initialisation, de paramétrage et de contrôle. Toutefois les actions seront dépendantes du type d'automates, ceux-ci se classant en trois grandes catégories :

- automates sans intervention humaine sur les résultats des traitements,
- automates dont les sorties peuvent être modifiées par l'opérateur,
- automates qui suggèrent des choix, l'opérateur devant choisir pour valider ou rejeter la ou les solutions proposées.

Ces catégories peuvent elles-mêmes se scinder en deux sous catégories :

- automates figés, dont les paramètres de fonctionnement sont prédéterminés et non modifiables par l'opérateur.
- automates contraints, où les paramètres ont été définis a priori mais où l'opérateur peut modifier les valeurs d'entrée selon le contexte.

On peut ainsi aboutir à un ensemble très complexe selon la nature des automates en fonctionnement et de l'interaction avec l'opérateur. Il est également important de noter que le degré d'expérience de l'opérateur va jouer un rôle primordial. Il apparaît que les opérateurs les plus expérimentés tirent généralement les plus de bénéfice des assistances apportées par les automates. De par l'expérience qu'ils possèdent, ils sont mieux à même de comprendre et d'utiliser les recommandations ou les solutions proposées, même si elles ne correspondent pas entièrement à ce qu'ils attendent du fait justement de leur expérience. Les débutants qui souvent maîtrisent moins bien la finalité du système n'utilisent pas les automates avec le même sentiment de faire corps avec la machine, d'où une moindre efficacité du couple homme-système.

Cet ensemble de points justifie, si besoin en était, le recours à de la simulation afin de mieux évaluer l'impact des choix d'aides à la décision sur les comportements des opérateurs.

2.3 Système communicant

Par essence, Un C3I ne fonctionne pas en tant que système isolé. Il en va de même pour une simulation de C3I. Les informations issues d'autres systèmes ou capteurs peuvent être simulées ou prises dans le monde réel. De même, les ordres issus de l'opérateur (simulé ou non) du C3I simulé doivent recevoir un écho extérieur (compte-rendu, changement dans les flux d'information entrants. Là encore les entités destinataires peuvent être simulées ou réelles.

Pour communiquer avec des systèmes réels, on utilisera les liaisons opérationnels et pour communiquer avec des systèmes simulés distants on utilisera des technologies existantes ou en cours de standardisation (ALSP, DIS). Si le modèle de C3I fait lui-même partie d'une simulation constructive, les communications seront simulées.

3. Simulation, aide à la décision et facteur humain : une démarche

3.1 Du constructif au virtuel, du virtuel au réel.

La démarche que nous proposons n'échappe pas à une phase initiale d'analyse du besoin mais réduit celle-ci au strict nécessaire à l'élaboration d'un premier modèle grossier.

Ce premier modèle est intégré à une ou des simulations technico-opérationnelles et étudié jusqu'à obtenir une spécification plus détaillée et mieux validée.

Cet objectif atteint après un certain nombre d'itérations peu coûteuses, on passe à une modélisation plus fine pouvant opérer éventuellement en temps réel. Des opérateurs humains ainsi que des systèmes ou composants réels peuvent commencer à intervenir. Cette étape peu donner lieu à des retours sur la spécification, mais son produit essentiel est la conception architecturale du système.

A la fin de cette phase, la spécification est totalement validée, et le système à demi conçu.

La dernière phase est une transformation progressive du simulateur en système réel. C'est à ce stade que s'effectuent les choix technologiques déterminants en matière de coûts, donc le plus tard possible.

3.2 La phase amont, le tout numérique

La première version du modèle de C3I, destinée à être intégrée à une simulation à grande échelle, sera une traduction naïve de l'analyse fonctionnelle préalable : simulation de sous-systèmes fonctionnels parfaits dans un premier temps (pour valider la première analyse; à ce stade, le modèle sera surtout un nœud de communication), puis, le besoin validé, on affinera la simulation de manière à représenter l'architecture du futur C3I.

S'agissant de modéliser un système à opérateurs humains, l'inconvénient ici est de ne pouvoir intégrer un opérateur humain (fonctionnement non temps-réel, haute répétabilité). Il sera donc modélisé de manière appropriée,

et ce qui peut se faire de mieux n'est que le moins mal possible.

En fait, on se trouve confronté à la définition d'un modèle de comportement d'opérateur qui restera invariant et dont les réactions face à des tâches nouvelles sont déduites de situations approchantes. Les risques de biais sont dans ce cas très importants et on doit considérer le modèle résultant comme un outil de prédéfinition servant au dimensionnement du système.

3.3 L'approche du réel, l'homme dans la boucle

La définition des IHM, rendue nécessaire par la présence de l'homme dans la boucle, suppose une analyse préalable des besoins opérationnels et des moyens disponibles.

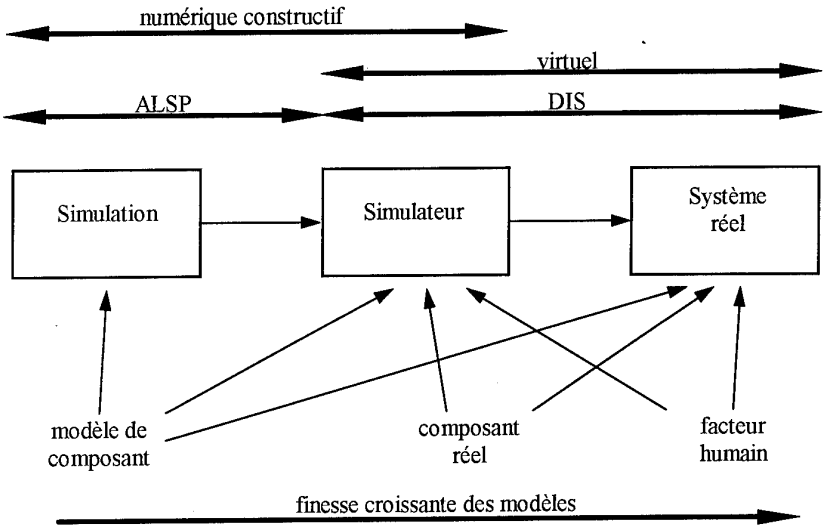
La recherche des informations à présenter selon le contexte, la structure des écrans ainsi que les modalités de dialogue vont résulter de la définition des tâches prescrites. Il convient également d'inférer un comportement théorique de l'opérateur face aux tâches à accomplir et de prendre en compte les besoins d'anticipation ainsi que les contraintes temporelles de chaque tâche.

Le maquettage des solutions IHM constitue une étape indispensable pour en permettre la validation par des opérateurs en termes de compréhension des modalités d'affichage et d'organisation des écrans.

3.4 Les outils : l'approche objet, l'évaluation ergonomique

La caractéristique majeure d'une simulation à évolution progressive devant aboutir en un produit final opérationnel est la qualité de son architecture de base. Elle suppose dès le départ la présence d'une épine dorsale à la fois logicielle et méthodologique.

Le squelette méthodologique sera la démarche de conception et de développement objet, l'épine dorsale logicielle sera une norme de communication entre objets éventuellement répartis (CORBA nous semble un exemple très prometteur à cet égard).



Il conviendra d'éviter le foisonnement d'objets « à plat » lors de l'évolution du C3I simulé : les objets « fonctionnels » apparus à la naissance du système devront servir chacun d'espace de développement à des objets enfants engendrés par le besoin grandissant de détail. Cette façon de faire présente une ressemblance trompeuse avec la méthode HOOD (Hierarchical Object Oriented Design) à cause de son caractère incrémental et dynamique.

La présence de l'opérateur humain dans la boucle suppose qu'on puisse en évaluer au mieux le comportement. Ce point reste souvent peu, voire pas abordé dans les résultats des simulations. Les comptes-rendus portent en effet bien souvent uniquement sur une évaluation de l'ergonomie « de surface », correspondant à la taille et à la couleur des symboles et des caractères, complétée par un avis global sur la simulation.

L'abord de la compréhension effective du fonctionnement du système, l'identification des modes opératoires ainsi que la notion de confiance dans les automates ou dans les outils d'aides constituent pourtant des éléments essentiels. Ils peuvent être examinés par l'étude du comportement effectif

de l'opérateur face à des scénarios de test, construits pour évaluer un ou plusieurs points clés d'ergonomie : besoin d'anticipation, délai pour une prise de décision, ... Ceci suppose une démarche d'évaluation ergonomique avec les étapes suivantes : identification a priori des points clés à évaluer, définition des séquences de tests à intégrer dans un scénario de simulation, description du comportement théorique attendu en termes d'actions opérateurs et de modalités de dialogue, observation des actions pendant les simulations avec enregistrement des traces informatiques, entretiens « à chaud » semi-ouverts pour faire verbaliser les enchaînements d'actions et décrire les difficultés rencontrées. La confrontations des comportements attendu et réel, l'analyse des erreurs ou des omissions ainsi que la reconstruction des modes opératoires effectifs vont permettre de qualifier in fine l'efficacité de la coopération homme-système.

4. Conclusion

Ces quelques lignes se veulent des éléments de réflexion pour la définition d'un futur atelier de production - ce terme couvrant tout le cycle de vie - de C3I.
Des sous-produits intéressants de cette ligne de développement pourront être des entraîneurs tactiques.

La démarche ébauchée permettra de réduire considérablement les coûts de développement tout en assurant une conformité maximale au besoin.

Elle permet également de prendre en compte les aspects de comportement des opérateurs confrontés à un nouveau système, d'évaluer leurs difficultés de compréhension (aide à la préparation des formations), leurs délais de réponse pour une bonne réaction ainsi que leur confiance probable dans les automates.

CONSTITUTION D'UN RÉFÉRENTIEL TERRAIN POUR LES ENGAGEMENTS EXTÉRIEURS

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INTRODUCTION

Pour répondre au besoin des opérationnel en matière de données géographiques, SAGEM à lancé une étude sur la constitution d'un référentiel terrain en engagements extérieurs.

En effet, pour assurer la réussite d'une mission lors d'engagements extérieurs, les opérationnels ont besoin de disposer de données géographiques vecteur fiables, nécessaires pour les SIC (Systèmes Informatiques de Commandement) .

POSITION DU PROBLÈME

L'objectif de cette étude est d'analyser et de définir un système de préparation de données terrain permettant de répondre au besoin opérationnel dans un contexte temps de crise, et pour des zones d'étendue limitée hors Centre-Europe.

Les données terrain sont destinées à alimenter les SIC, ce qui impose d'adopter un format de données standard. En l'occurrence, nous nous sommes appuyés sur DIGEST, qui est la norme officielle OTAN pour l'échange de données géographiques.

Le type de données retenu est le vectoriel renseigné ou attribué, ce qui permet d'une part de les visualiser, et d'autre part de les interroger. Par exemple, il est possible, pour une piste aérienne, de savoir quelle est sa longueur, sa largeur, son orientation et son revêtement.

La zone traitée, dans la première phase de l'étude, est d'étendue limitée (de l'ordre de 100 km par 100 km). Le niveau de détail des données est de l'ordre de ce que l'on trouve sur une carte au 1:50.000.

Le contexte "temps de crise" implique un temps de réponse court et une approche itérative (fourniture de lots de données intermédiaires sans attendre la fin de la préparation des données).

Les régions du monde, hors Centre-Europe, susceptibles d'un engagement des forces armées, sont souvent mal cartographiées, et ne bénéficient pas d'un travail de fond de production d'une base de données cartographiques, comme c'est le cas pour le territoire national. Les données disponibles sur ces zones sont très dépouillées, et il est nécessaire de les enrichir, sur une zone limitée en superficie, pendant le bref délai de la montée en puissance.

DÉMARCHE DE L'ÉTUDE

L'étude s'est déroulée selon les phases suivantes :

- rencontre avec les opérationnels pour formaliser le besoin,
- analyse des données sources, d'une part celles disponibles en métropole et d'autre part celles accessibles sur place : cartes papier, images satellitaires, données thématiques, renseignements opérationnels, données vectorielles,
- définition du modèle de données du référentiel terrain à partir de l'analyse de besoin, du modèle de référence, du modèle issu des cartes papier, du modèle de photo-interprétation des images,
- synthèse des méthodes à mettre en oeuvre pour constituer le référentiel terrain à partir des données sources,
- synthèse du besoin réalisable.

L'étude s'est appuyée sur un cas concret et a pris en compte des données réelles en quantité et en qualité.

ANALYSE DU BESOIN

Le besoin a été indiqué par des opérationnels au cours de plusieurs réunions de recueil du besoin.

Il est apparu primordial d'avoir rapidement des données sur la zone, même si elles sont incomplètes ou géographiquement imparfaites. De même, les données thématiques sont souvent très importantes (par exemple, la répartition géographique des groupes ethniques).

Le besoin des opérationnels a été exprimé sous forme d'une classification en thèmes, sous-thèmes, objets, avec pour chaque objet un ensemble de caractéristiques liées à l'emploi.

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

Les thèmes sont :

- données géographiques (hypsographie, géologie, hydrographie, couverture végétale, climatologie),
- voies de communication (voies routières, voies ferrées, voies maritimes, voies navigables et voies aériennes),
- infrastructures (zones construites, équipements de communications, principaux bâtiments comme les hôtels, les hôpitaux, les écoles, les casernes, les représentations diplomatiques, ...),
- économie (lignes électriques, sites industriels, dépôts de carburant, ...),
- démographie (répartitions géographiques des groupes ethniques et des courants religieux, populations étrangères, langues, ...).

On trouve donc deux types de données : des données à caractère géographique, et des données à caractère thématique.

DONNÉES SOURCES

Les "données sources" sont les éléments qui vont servir de matière première pour constituer le référentiel terrain.

L'analyse des données sources a permis d'identifier les sources suivantes :

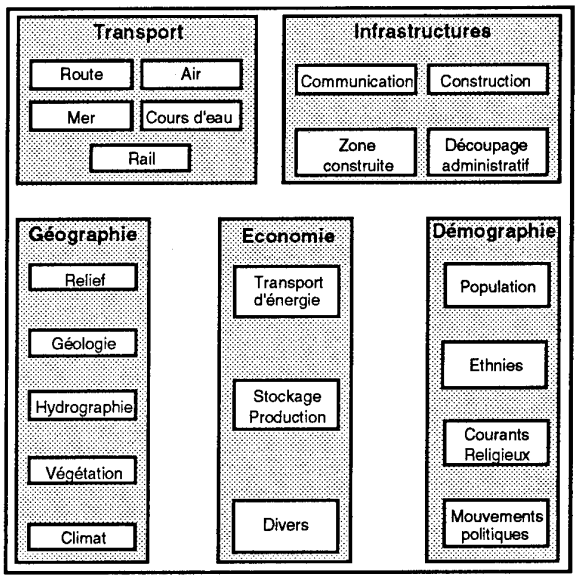
- les cartes générales de type IGN, à petites, moyennes, et grandes échelles. Les cartes à petites échelles ne sont pas assez détaillées pour être intéressantes. Les cartes à moyennes échelles sont en général relativement récentes, et peuvent servir de base de départ à la constitution du référentiel terrain. Les cartes à grandes échelles seraient idéales, mais elles sont souvent anciennes (cartes de plus de 40 ans par exemple), ou incomplètes (avec des zones blanches non cartographiées), ou même inexistantes,
- les cartes thématiques à petites échelles et les données encyclopédiques, dont on peut disposer sous forme papier ou sous forme numériques sur CDROM. On trouve des cartes de relief, de type de sol, climatologiques, hydrographiques, démographiques, ...,
- la cartographie vectorielle, encore peu développée, comprenant le DCW disponible sur le monde entier, mais pas très intéressant du fait de son échelle au 1/1.000.000, et le DFAD, plus intéressant du fait de son échelle au 1/250.000 ou 1/50.000, mais qui n'est en général pas disponible dans les zones à traiter,
- les cartes à surcharge aéronautiques de la DMA (1/5.000.000 à 1/250.000),
- les images de télédétection (SPOT, LANDSAT),
- les images radar (ERS1),
- les photographies aériennes, qui peuvent aider à l'interprétation des images satellites en levée de doute,
- les documents touristiques, c'est-à-dire des cartes touristiques, en général récentes, des guides de voyage, des plans de ville,
- les données opérationnelles, images de reconnaissance aérienne ou de drône, dossier d'objectif, ...

MODÈLE DE DONNÉES

Le modèle de données a été élaboré à partir :

- de l'analyse du besoin des opérationnels,
- des modèles de données sources (légende dans le cas des cartes papier, modèle de photo-interprétation pour les images satellitaires et les photographies aériennes, ...),
- du modèle de référence (DIGEST v1.2).

Le squelette du modèle de données (thèmes et sous-thèmes) est indiqué dans la figure qui suit :



Chaque sous-thème est constitué d'une collection d'objets (par exemple, route) auxquels sont affectés des attributs (par exemple, largeur, composition de la surface, période d'utilisation, pratiquabilité, ...).

Les attributs retenus sont :

- soit des attributs retenus par DIGEST pour l'objet considéré (par exemple, composition de la surface),
- soit des attributs utilisés dans DIGEST, mais pour d'autres objets (par exemple, période d'utilisation),
- soit des attributs n'existant pas dans DIGEST (par exemple, pratiquabilité).

Le modèle de données a été mis en forme sous forme de fiches, une fiche par objet, les fiches étant remplies sur papier ou sur écran pendant la phase d'élaboration.

On s'est attaché à ne prendre en compte que le besoin réalisable, c'est-à-dire à ne pas mettre dans le modèle de données des objets ou des attributs que l'on ne saura pas renseigner.

MÉTHODES DE PRODUCTION

Les méthodes de production vont permettre de passer des données sources à un lot de données destinées à être chargées dans un SIC. Les méthodes vont être mises en oeuvre sur un équipement informatique de type station de travail, en utilisant des outils du commerce.

Les différentes phases sont :

- l'acquisition qui peut se faire par pilotage d'un scanner pour les documents papier, ou par support des formats standards pour les données sous forme numériques (par exemple, les formats DIGEST USRP pour des données Raster, DCW pour les données vecteurs, le format SPOT Image),
- les pré-traitements géométriques qui consistent à repérer géographiquement les données, puis à les projeter dans un référentiel unique, de façon à rendre les diverses données sources cohérentes et superposables d'un point de vue géographique,
- les pré-traitements radiométriques qui permettent d'améliorer la qualité d'affichage des données sources, pour faciliter les phases d'élaboration,
- la vectorisation qui peut se faire sur papier ou sur écran.

  Dans la méthode papier, les vecteurs sont tracés sur calque par un opérateur, le calque étant déplacé sur les différents documents sources disponibles, l'attribution des vecteurs se faisant sur des fiches papier.

  Dans un deuxième temps, le calque est vectorisé à l'aide d'un outil de vectorisation automatique, et le contenu des fiches papier est saisi.

  Dans la méthode sur écran, l'opérateur génère les vecteurs à partir d'un fond de carte numérisé en utilisant un outil de vectorisation semi-automatique, et renseigne simultanément les vecteurs. Cette deuxième méthode est plus rapide que la précédente, mais nécessite un opérateur plus qualifié,

- le renseignement qui va permettre d'attribuer les vecteurs, pendant ou après la vectorisation,
- la mise à disposition qui consiste à sélectionner dans la base de données vecteur un ou plusieurs thèmes pour une zone géographique donnée, et à les exporter en format d'échanges DIGEST, pour alimenter le SIC.

BESOIN RÉALISABLE

On peut distinguer trois phases d'utilisation de cette étude : le système "métropole", le système "projeté" et le système "projeté 3D".

Système "métropole"

Le système "métropole" est utilisé avant que les opérationnels ne soient présents sur le terrain. Il est constitué par des personnels spécialistes, et peut mettre en oeuvre des moyens "lourds" (scanner grand format, traceur, restituteur, ...), soit directement, soit en faisant appel aux ateliers de production de données géographiques.

Les données sources exploitées sont celles disponibles en métropole :

- des cartes papier moyennes échelles,
- des cartes papier grandes échelles, si elles existent,
- des images satellitaires, une fois approvisionnées,
- des données encyclopédiques.

La zone qui a servi de support à l'étude est située sur le continent africain. Sur cette zone de 100 km sur 100 km, une couverture cartographique complète au 1:50.000 était immédiatement disponible, mais les cartes étaient pour la plupart anciennes (environ 40 ans).

Une couverture partielle en images satellitaires (SPOT et LANDSAT) a été approvisionnée, mais ces données n'ont été disponibles que bien après les cartes papier, la procédure étant plus complexe (choix des scènes, commande, acheminement des données). Une situation réelle de crise permettrait de réduire ce délai.

La réalisation du référentiel terrain a débuté à partir des cartes papier, qui ont permis d'extraire les réseaux (routes, pistes, voies ferrées, rivières, trait de côte), l'hydrographie et l'emprise des villages.

Les images satellitaires ont ensuite permis de corriger (plantation disparue, village dont l'emprise a varié, ...) et de compléter (nouveaux réseaux, lignes électriques par exemple, nouvelle plantation, ...) le référentiel terrain.

Système "projeté"

Le système "projeté" est utilisé sur le terrain. Les personnels qui le mettent en oeuvre, s'ils ont reçu une formation (cartographie, photo-interprétation, ...), ne sont pas nécessairement des spécialistes géographes. Les moyens à leur disposition sont limités (scanner petit format, imprimante, station de traitement, ...).

Les données sources sont celles disponibles sur place (cartes papier réalisées par les instituts géographiques locaux, plans de réseaux, données recueillies sur le terrain, images de reconnaissance, ...).

Pour la zone qui a servi de support à l'étude, des données sources complémentaires ont pu être approvisionnées sur place : couverture cartographique récente mais partielle au 1:25.000, photographies aériennes, plans, données à caractère thématique (livres d'école par exemple), couples de photographies stéréoscopiques (pour déterminer un Modèle Numérique de Terrain dans les zones urbaines).

Les données issues du système "projeté" sont au format vecteur, elles constituent du $2D^{1/2}$. Chaque objet est défini par des attributs descriptifs ainsi que par sa hauteur.

Système "projeté 3D"

Le système "projeté 3D" est utilisé sur le terrain, il vient en complément du système "projeté". A partir des données recueillies lors de la constitution du référentiel terrain "projeté", (Modèle numérique de terrain, données vecteur), les opérationnels vont constituer un référentiel 3D. A partir de ces données, les opérationnels peuvent obtenir une vue 3D réaliste des villes et pour faciliter le suivi et la préparation des missions.

CONCLUSION

L'approvisionnement en données terrain des SIC est un besoin primordial. Pour les engagements extérieurs hors Centre-Europe, ce type de données n'existe pas, et l'étude constitution d'un référentiel terrain pour les engagements extérieurs est une réponse à la demande des opérationnels.

A Weather Forecast Utility Model for Military Missions

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SUMMARY

The weather FORecast Utility Model (FORUM) is being developed to analyze the benefit of forecast data to the operational commander in the field. To be relevant to a given operation, such a model must reflect the concept of operations (CONOPs) of the mission under study. Thus, the modeler must understand the operation's decision process, and, in particular, how weather data influences that process. Toward that end, the description of FORUM is illustrated by an air munitions mission, wherein both the go/no-go decision and a tactical payload alternative are decided on the basis of weather parameter predictions. Single target mission effectiveness is cast in the form of sorties used and days needed to complete the mission which, in this case, is ground target destruction. For multiple weapon/target site scenarios, effectiveness can also be expressed as targets killed within a fixed period of time or resources needed to negate a fixed number of targets. For multitarget scenarios, the force multiplicative effects of correct forecast data is manifested via such metrics.

The weather parameter data being used to characterize forecast accuracy is the product of some very detailed analyses and simulation of the forecast process from satellite measurement through weather parameter prediction. The Forecast Systems Laboratory (FSL) of the U.S. National Oceanic and Atmospheric Administration (NOAA) is providing satellite measurement simulation and weather parameter prediction for a sample case within the continental United States. The statistical characterization of this data provides some of the input for the FORUM model.

INTRODUCTION

The effects of weather on military missions is historic and ongoing. From the days of the Spanish Armada through the D-Day landings in Europe to present day difficulties in flying NATO missions over Serbian territory, weather has played a decisive role in military mission performance. The advent of improved all-weather sensors and combat equipment mitigates, but does not supersede, the need for accurate, timely weather forecast data to aid the commander's planning process.

This paper describes a utility model that quantifies the effectiveness of weather forecast data applied to military mission planning. The models described include effects of satellite data measurement, the forecast process and its accuracy and timeliness, military mission CONcepts of OPeration (CONOPs), military weapon systems performance, and the effects of nominal weather conditions. Mission effectiveness is calculated in metrics of interest to the field commander in that they relate to resources expended including time and assets. Sensitivity to those Measures of Effectiveness (MOEs) by the weather conditions and forecast accuracy lead to rationale for setting requirements on forecast process and the data that supports it.

The end-to-end modeling and analysis process will be described in sequence order of processing. This starts with the processing of satellite measurement data to the point of generating forecasts of specific weather parameters over a range of prediction times up to 12 hours in advance. The accuracy of these parameter forecasts is characterized by statistical comparison with truth values obtained by calibrated ground and air station sensors. The forecast and truth data serve as input to the processes of predicting cloud cover, visibility, and the thermal environment experienced within the military combat zone. Models of the specific military mission take into account planning CONOPs, systems performance (e.g., sensors and weapons), and the influence of true weather conditions and forecast accuracy.

To motivate and illustrate the models and analysis procedures, a specific mission is analyzed: that of tactical air munitions drops on fixed ground targets. Focusing on this specific mission allows visibility of how mission-specific CONOPs and system performance influences mission effectiveness. Exclusive of these effects, however, the upfront data processing and top-level utility models are applicable to a broad range of military (and civil) missions that can be supported by weather forecast data.

Parametric results about a baseline set of conditions show the sensitivity of mission MOEs to weather forecast accuracy, weather conditions, and mission-specific systems performance. These sensitivities suggest procedures for establishing requirements of satellite measurement accuracies and the total accuracy of the forecast process.

THE DATA FLOW PROCESS

The volume of data per unit time flowing from the source sensor measurements aboard the Air Force's Defense Meteorological Satellite Program (DMSP) satellite is very sizable. This satellite provides optical and microwave measurements of the atmosphere in both temporal and spatial extent as it passes over the earth's surface in low earth orbit. The purpose of the utility study is to model and simulate (end-to-end) the weather measurement to mission effectiveness process. Figure 1 shows notionally the principal analysis functions along this path. As the satellite data passes from left to right, the processing steps distill the information content and reduce the data rate from the megabytes per second collected by the sensors to the several scalar MOEs that quantify mission performance over the mission timeline.

It is beyond the scope of this paper to describe in detail each of the upfront weather data processing algorithms. Rather, the primary functions of these processes and their input/output interfaces will be described with reference to descriptive documentation where appropriate. The Aerospace Corporation (Aerospace), which provides General Systems Engineering and Integration (GSE&I) services to the U.S. Air Force's Space and Missile Systems Center, and the National Oceanic and

Paper presented at the AGARD MSP 3rd Symposium on "Tactical Aerospace C³I in Coming Years", held in Lisbon, Portugal from 15th May to 18th May 1995, and published in CP-557.

Atmospheric Administration's (NOAA) Forecast Systems Laboratory (FSL) have cooperated in the analysis flow, as shown in Figure 1.

The FSL has simulated DMSP weather satellite data and processed it with calibrated ground and airborne sensor data to provide weather parameter forecasts and parameter truth values for a 24-hour span of time representing the meteorological events of September 15, 1993 over the central portion of the United States (Ref. 1). A rectilinear data grid of 140-by-140 cells at 21 altitudes is projected onto a polar stereographic map over this region as shown in Figure 2. The horizontal cells were about 12.1 km per side and the vertical cell height was 1 km.

The truth or control weather conditions were first established over this grid at 15-minute intervals starting at midnight Greenwich Mean Time (GMT)[1] on September 15. This control grid in space and time was created by running the Regional Atmospheric Modeling Simulation (RAMS) (Refs. 2 and 3) simulation with local and boundary condition inputs supplied by hourly ground and occasional airborne sensor measurements of weather parameters over the 24-hour period. The RAMS program propagated these conditions to all interior grid points over that time span. Figure 3 shows a typical 3-dimensional plot of truth temperature in degrees Kelvin at zero altitude over the horizontal grid.

The satellite-reconstructed weather parameters over the spatial grid are created by an FSL simulation, which provides temperature and moisture fields. The temperature fields are degraded by randomly generated variations about the truth temperature. Such pseudo-satellite-generated values serve to corrupt the control values at the 12-hour mark past midnight, which is the starting point for the forecast data provided in 15-minute increments up to 12 hours after this reference time or 24 hours past midnight on September 15. Thus, the forecast grid starts with the truth (control) parameter values and corrupts them in a way consistent with satellite-generated weather parameters at the 12:00 noon point in time. The forecast grid, past noon, propagates these values forward every 15 minutes to the next midnight (i.e., the forecast runs from noon on the 15th through midnight on the 16th in 15-minute increments). The atmospheric temperature and moisture are calculated at the 12-hour point to simulate the satellite-reconstructed values. From these parameters, winds and cloud height fields are calculated geostrophically and hydrostatically. The 12-hour parameter grid then serves to initialize a forward weather propagation in time in 15-minute increments up to the 24-hour grid cutoff point.

At the end of this processing by FSL, two temporal/spatial weather grids exist:

- the truth (control) grid, which runs 24 hours in 15-minute increments midnight GMT on September 15 to the following midnight
- the forecast grid, which is the same as the truth grid for the first 12 hours, and then provides satellite-generated parameter forecasts from the 12-hour point to the following midnight

Both the truth and forecast databases are used by the military utility models developed and used by Aerospace. These databases contain 140-by-140-by-21 spatial gridpoints at 15-minute increments over a 24-hour period. They represent many megabytes of data. The weather parameters reported at each grid point include:

- temperature (dry bulb and dew point)
- pressure
- wind (direction and speed)
- cloud mixing ratio (CMR)
- visibility
- total precipitation

Figure 1 now shows both truth and forecast weather parameter databases as delivered to Aerospace by FSL. At this point, the parameter values for both truth and forecast are passed forward to three separate analysis efforts labeled Military Utility Model Interface in Figure 1. These tasks provide:

- statistical characterization of the difference error between the truth and forecast databases
- construction of cloud regions and computation of line of sight viewing and cloud extent statistics
- initialization of a precision-guided munitions simulation called Electro-optical Tactical Decision Aid (EOTDA) (Ref. 4)

Descriptions of the latter two tasks will be deferred to the sections on Military Utility Modeling, because they depend on the particular military mission, which is the subject of this paper.

The first task is to characterize the forecast parameter error by calculating sample statistics of the mean and standard deviation. Figure 4 shows a sample mean and standard deviation plot for temperature error versus forecast time over a 6-hour span from the forecast starting point. The solid curve represents sample error mean, and the dotted curves represent mean $\pm$ 1 standard deviation taken over a 100-by-100 inner grid of horizontal position cells at a fixed altitude. The sample is limited to this inner subgrid because the forecast propagation process is, in time, corrupted by ground truth boundary conditions at the edges of the 140-by-140 supergrid over which the forecast is propagated. These same sample statistics on error are calculated for each weather parameter in the FSL database in order to characterize weather forecast accuracy for future military utility analyses.

AN AIR MUNITIONS DROP MISSION

Before proceeding with the discussion of utility modeling and data flow, it is useful to describe a particular military mission. What follows will involve specific features of that mission and how weather data influences the decision process. The mission under consideration is that of tactical ground target bombing via aircraft munitions drops. The objective is to kill or negate enemy ground targets via air munitions drops. The basic choices for the flight commander are:

- whether to schedule an aircraft sortie for a particular target on a given day

[1] This corresponds to 6:00 p.m. Central Standard Time in the United States on September 14, 1993.

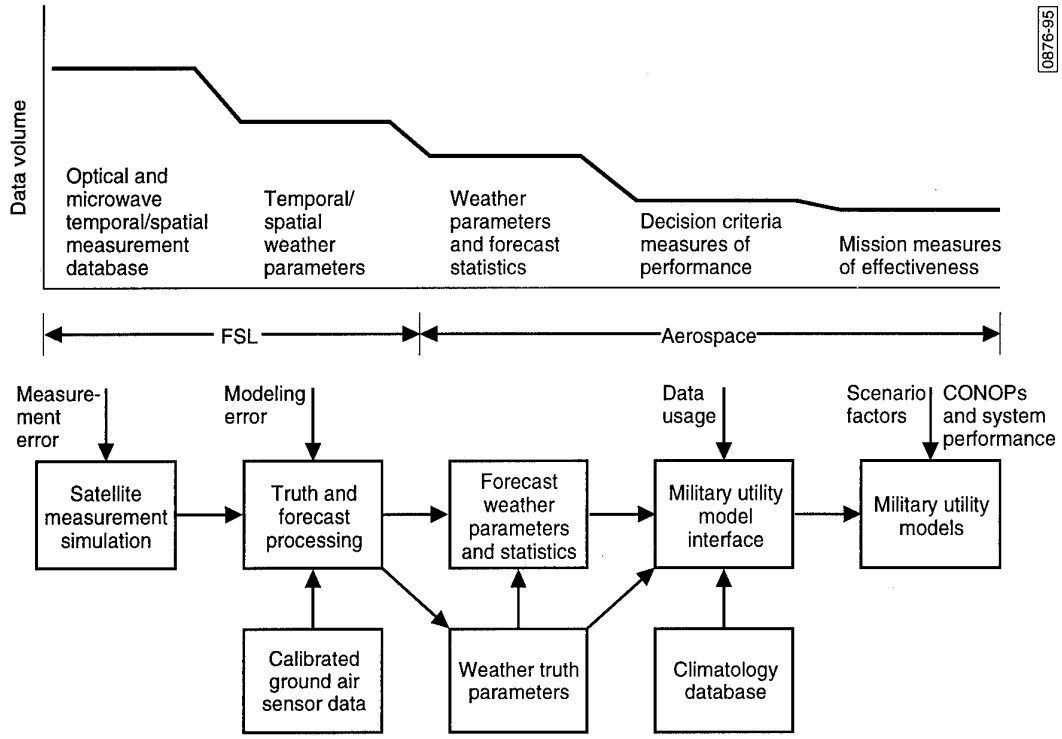


Figure 1. Military utility data flow overview.

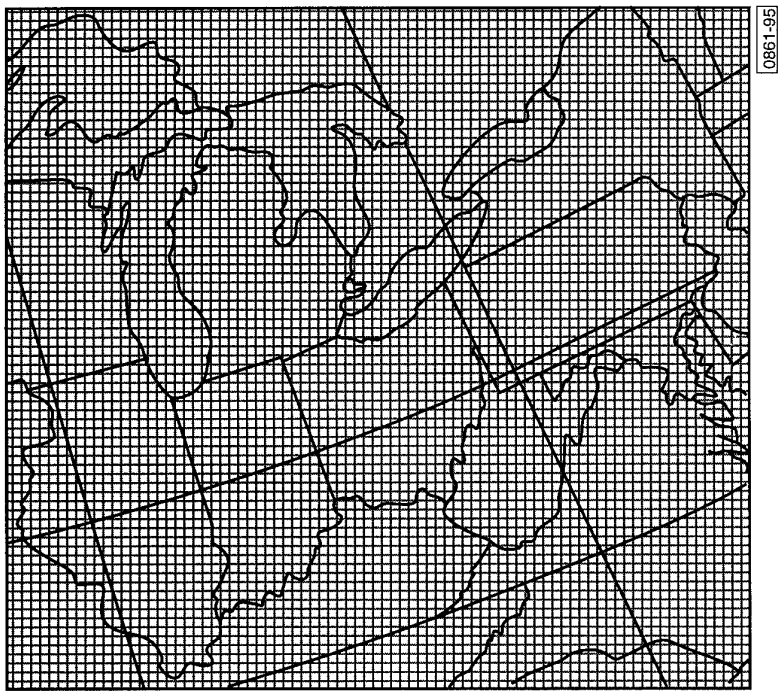


Figure 2. Data grid projected over the central United States.

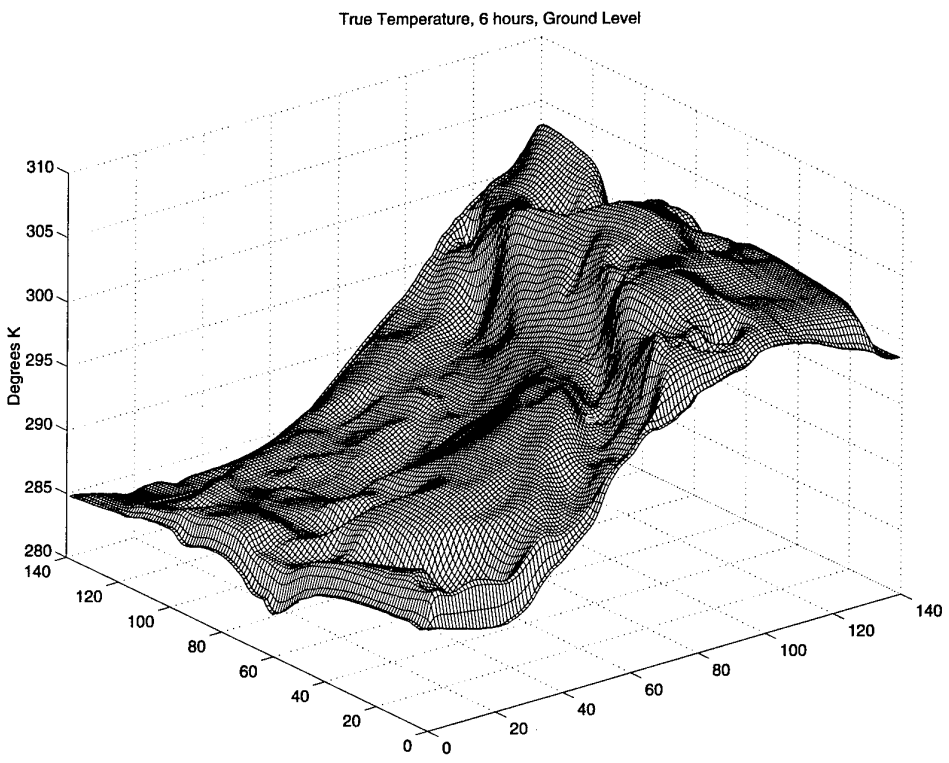


Figure 3. Temperature distribution over a horizontal grid.

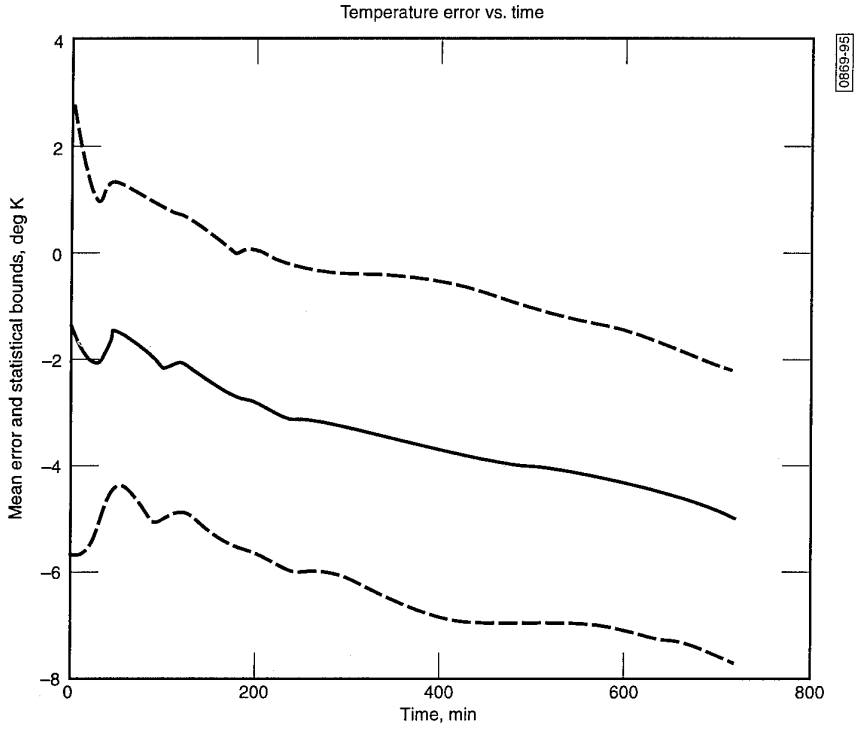


Figure 4. Weather parameter forecast accuracy.

- if scheduled, the type of munition to use:
  - gravity bombs
  - precision-guided munitions (PGMs)

Figure 5 depicts the scenario. The advantage of correct sortie/target site pairing is to be found in fewer aborted or ineffectual attack sorties that may result from unfavorable weather conditions over the target site. The mission elements consist of the forward command and control center making the assignment, attack aircraft, bomb load, and target site.

During a normal 24-hour attack cycle, mission planning will be completed at 6:00 a.m. local time for an attack plan executed that day, and the process will be repeated on a daily basis during the campaign. The daily decision and attack process (Ref. 5) is summarized by the flow shown in Figure 6. At the start of mission planning (upper left corner), a go/no-go decision is made based on whether the cloud ceiling height (CH) exceeds 10,000 ft[1] over the target site. If so, a go-ahead is given for the mission. If not, the target is recycled to the next day's plan. The next decision after go-ahead is the selection of a bomb load between gravity bomb and PGM alternatives. PGM is chosen if predicted cloud cover (CC) over the region is less than 3/8 of the sky.

Once the sortie is launched, there are five possible paths of action over the target site:

- CH is below 10,000 ft, in which case the mission is aborted (this simplified model does not account for secondary or tertiary target options)
- CH is above 10,000 ft, PGMs are loaded, and actual CC below ceiling is less than 3/8 (i.e., correct bomb choice)
- CH is above 10,000 ft, gravity bombs are loaded, and actual CC below ceiling is greater than 3/8 (i.e., correct bomb choice)
- CH is above 10,000 ft, PGMs are loaded, and cover below ceiling is greater than 3/8 (i.e., wrong bomb choice)
- CH is above 120,000 ft, gravity bombs are loaded, and cover below ceiling is less than 3/8 (i.e., wrong bomb choice)

Any of the four paths resulting in attack can result in target negation or survival. The probabilities of their result vary with the load type and the actual weather conditions over the target site.

Since early negation of a given target site and the resources used are of importance to the field commander, the MOEs for this mission are:

- total sorties flown per kill
- number of days elapsed per kill
- number of target kills among a fixed set within a fixed number of days
- sorties (days) required to negate a fixed number of targets

The model descriptions to follow use the weather forecast information, stated concept of operations, and weapon system performance to evaluate the above stated MOEs for both single target and multitarget scenarios.

MILITARY UTILITY MODELING

Now consider a probabilistic model of the air munitions drop mission for a single attack aircraft/target pairing. This model provides the expected number of days to target kill and the sorties flown via a closed form algebraic relation. The simplicity of the model provides insight to the dependency of mission effectiveness on weather forecast accuracy, nominal weather conditions, and the mission CONOPs and weapon systems performance. A more general Monte Carlo analysis of multiple attack/target pairings can then be developed from the probability functions of the single attack/target model, and restrictive analytical assumptions can be relaxed in the process.

This model, which will be called the FORecast Utility Model (FORUM), uses results generated by other weather parameter and weapon performance analyses and simulations which will be described below. The overarching model name FORUM encompasses a number of separate analyses which are somewhat specific to the air drop mission. The top-level FORUM model, however, has applicability to a broad range of military and civilian missions.

THE SINGLE TARGET MODEL

The FORUM model for a single target attack scenario seeks to quantify the number of sorties and elapsed days until a target can be negated under the assumption that one sortie (aircraft flyout or attack effort) can be mounted per day. This is based on usual CONOPs, wherein attack planning proceeds on a daily cycle using weather and intelligence/reconnaissance information on a cyclic basis (Ref. 5).

The probability density function for single target negation is given as (Ref. 6):

$$p(n,k) = \frac{(k-1)!}{(n-1)!(k-n)!}(p_1)^{(k-n)}(p_2)^{(n-1)}p_3 \qquad (1)$$

where

$p(n,k)$	=	probability target is negated in k days by n sorties
n	=	number of sortie attacks
k	=	number of days to negation
p_1	=	probability of no sortie being flown
p_2	=	probability of a failed sortie
p_3	=	probability of a successful sortie (i.e., target negation)

Note that Equation 1 assumes day-to-day independence of events, which is not correct for weather-related events. For now, this assumption will be allowed to stand in order to gain insight

[1] This conservative CH was characteristic of operations during Desert Storm to protect pilots against ground-to-air attack.

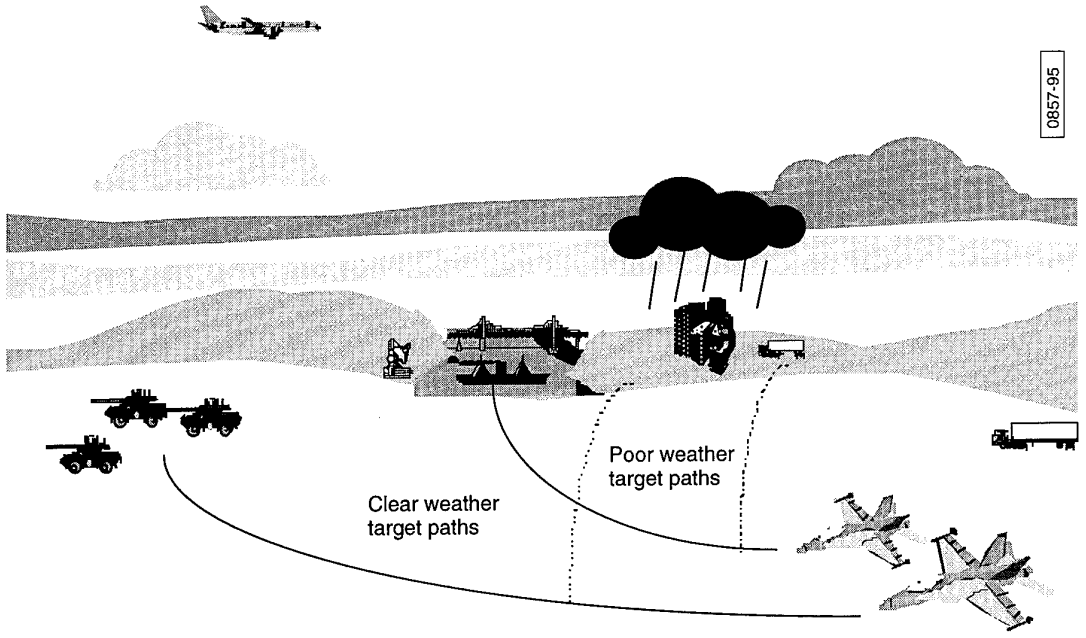


Figure 5. Air-dropped munitions scenario.

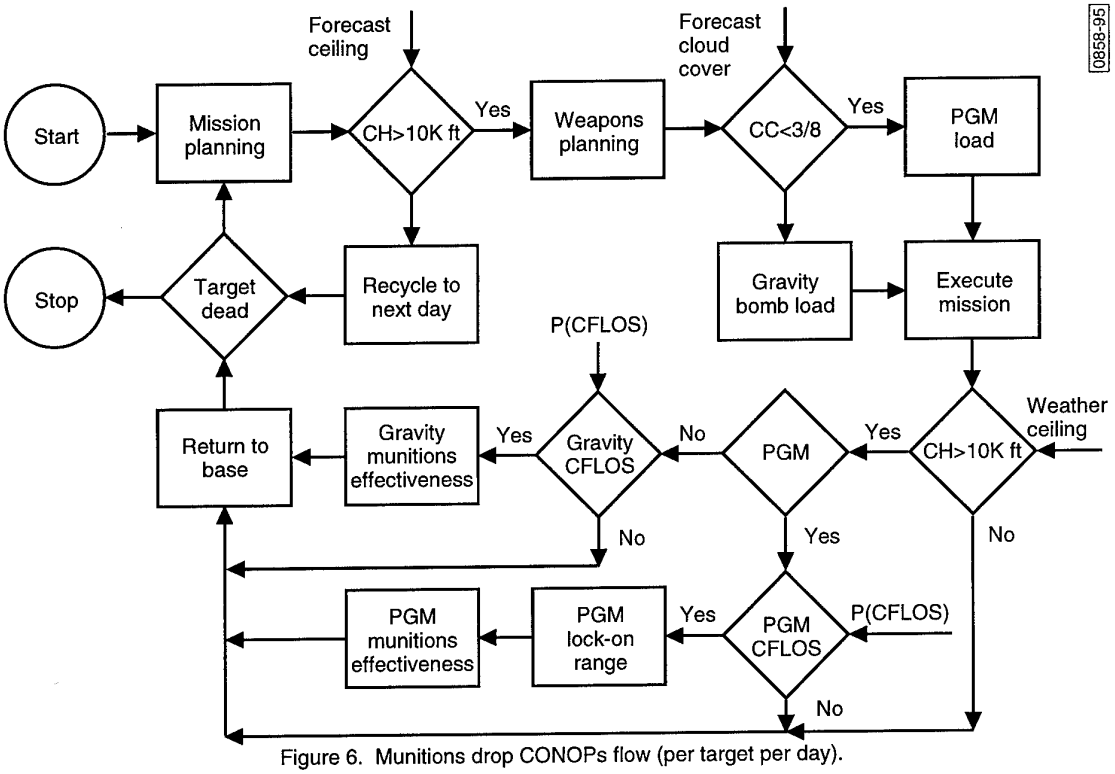


Figure 6. Munitions drop CONOPs flow (per target per day).

to the process. The Monte Carlo method to follow does not require this assumption, and day-to-day correlations can be included in the modeling technique.

WEATHER FORECAST USAGE AND EFFECT

The influence of weather forecasting on this process is via the notion of good and bad weather from a go/no-go planning perspective. The mission planner has threshold criteria by which he judges the readiness state of the mission. In the case of weather, these criteria are based on weather parameter values forecast for the target area at the planned engagement time. Thus, the above probabilities of sortie dispatch and success or failure are linked to weather and planning probabilities as follows:

$$\begin{aligned} p_1 &= \text{prob}[\text{no sortie}] \\ &= p_f\left(p_{g/b} + p_{b/b}\right) * p_{bf} \end{aligned} \tag{2}$$

$$\begin{aligned} p_2 &= \text{prob}[\text{failed sortie}] \\ &= \left(1 - p_{s/g}\right)\left(p_{g/g} * p_{gf} + p_{g/b} * p_{bf} * \left(1 - p_f\right)\right) \\ &\quad + \left(1 - p_{s/b}\right)\left(p_{b/g} * p_{gf} + p_{b/b} * p_{bf} * \left(1 - p_f\right)\right) \end{aligned} \tag{3}$$

$$\begin{aligned} p_3 &= \text{prob}[\text{successful sortie}] \\ &= p_{s/g}\left(p_{g/g} * p_{gf} + p_{g/b} * p_{bf}\left(1 - p_f\right)\right) \\ &\quad + p_{s/b}\left(p_{b/g} * p_{gf} + p_{b/b} * p_{bf}\left(1 - p_f\right)\right) \end{aligned} \tag{4}$$

where

- p_f = probability forecast information is used in mission planning ($p_f = 0$ means no forecast used)
- $p_{g/b}$ = probability target site has good weather given a bad weather forecast
- $p_{b/b}$ = probability target site has bad weather given a bad weather forecast
- $p_{g/g}$ = probability target site has good weather given a good weather forecast
- $p_{b/g}$ = probability target site has bad weather given a good weather forecast
- $p_{s/g}$ = probability of successful sortie given good weather at target site
- $p_{s/b}$ = probability of successful sortie given bad weather at target site
- p_{gf} = probability of good weather forecast
- p_{bf} = probability of bad weather forecast

In the context of the air munitions drop CONOPs, good and bad weather refers to the CH criterion.

FORECAST ACCURACY

Probabilities of good or bad weather at the target site given good or bad forecasts depend on the weather parameters used in the mission decision, accuracy of forecasting these parameter values, and criterion level of the weather parameters. Figure 7 shows notionally the relationships involved for a typical weather parameter. Here, the chosen parameter's distribution function P(x) has a criterion level C such that P(C) [the probability that $(x \le C)$] is the probability of good weather. The distribution function P_ε is that of the error between the estimate $\hat{x}$ and the actual weather value x. Thus, the probability of good weather given a good forecast $p_{g/g}$ is the normalized density weighted integral over all good weather conditions $\left[c_0 < x < C\right]$, of the probability of having a good forecast $\left(\text{i.e., } P_\varepsilon\left(C - x\right)\right)$.

Let us now assume that the weather density P(x) is constant over the criterion interval $\left[C_0, C\right]$. The Tchebycheff Inequality (Ref. 7) can be applied to the error distribution P_ε having standard deviation σ_ε, to yield:

$$1 - P_\varepsilon\left(C - x\right) \le \frac{{\sigma_\varepsilon}^2}{2\left(C - x\right)^2} \tag{5}$$

If $P_\varepsilon\left(C - x\right)$ is now approximated by Equation 5 to a minimum value of 1/2 (corresponding to such a large σ_ε that the probability of a good forecast is even with a bad forecast), then:

$$p_{g/g} \approx 1 - \frac{\sigma_\varepsilon}{\left(C - C_0\right)} + \frac{{\sigma_\varepsilon}^2}{2\left(C - C_0\right)^2} \tag{6}$$

$$\text{for } \left[0 \le \sigma_\varepsilon \le \left(C - C_0\right)\right]$$

This approximation converges to $p_{g/g} = 1$ for $\sigma_\varepsilon = 0$ [no forecast uncertainty] and to $p_{g/g} = 1/2$ for $\sigma_\varepsilon = \left(C - C_0\right)$ [largest forecast uncertainty]. Since $p_{g/g}$ and $p_{b/g}$ are mutually exclusive and complementary probabilities:

$$p_{b/g} = 1 - p_{g/g} \tag{7}$$

A similar line of reasoning using the bad weather region $\left[C \le x \le C_1\right]$ yields:

$$p_{b/b} \approx 1 - \frac{\sigma_\varepsilon}{\left(C_1 - C\right)} + \frac{{\sigma_\varepsilon}^2}{2\left(C_1 - C\right)^2} \tag{8}$$

and

$$p_{g/b} = 1 - p_{b/b} \tag{9}$$

WEAPON EFFECTIVENESS AT THE TARGET SITE

Once at the target site, the mission is aborted if the CH is below 10,000 ft (i.e., the ceiling forecast was wrong). If PGM weapons are on board, the probability of cloud free line of sight (CFLOS)

is used to determine if an unobscured target is visible. If not, the mission is aborted. The lock-on range, determined by the EOTDA simulation, is used to evaluate the CFLOS probability. If gravity bombs were loaded, the CFLOS probability determines whether or not they will be dropped. If the target is not killed by reason of weapon failure or sortie abort, it cycles to the next day's mission planning.

Now convert these CONOPs of Figure 6 to a model format. Equations 3 and 4 used the mission success probabilities given good and bad weather on target, $p_{s/g}$ and $p_{s/b}$, respectively. Here, good weather refers to CH, and by the mission CONOPs, $p_{s/b} = 0$, because the mission is aborted if the actual CH is below 10,000 ft. If the ceiling on target is good, there are four independent paths to success depending on the weapon load and the CC over the target area:

- PGM with CC ≤ 3/8 (CC forecast correct)
- PGM with CC > 3/8 (CC forecast incorrect)
- gravity bomb with CC ≤ 3/8 (CC forecast incorrect)
- gravity bomb with CC > 3/8 (CC forecast correct)

These paths translate to the following value for probability of success given good ceiling weather $p_{s/g}$:

$$\begin{aligned} p_{s/g} = &\left[1-\left(1-p_{kp}\right)BOT_{p/gc}\right]\bullet PCFLOS_{p/gc}\bullet p_{gc/gcf}\bullet p_{gcf} \\ &+\left[1-\left(1-p_{kp}\right)BOT_{p/bc}\right]\bullet PCFLOS_{p/bc}\bullet p_{bc/gcf}\bullet p_{gcf} \\ &+\left[1-\left(1-p_{kgb}\right)BOT_{gb}\right]PCFLOS_{gb/gc}\bullet p_{gc/bcf}\bullet p_{bcf} \\ &+\left[1-\left(1-p_{kgb}\right)BOT_{gb}\right]PCFLOS_{gb/bc}\bullet p_{bc/bcf}\bullet p_{bcf} \end{aligned} \quad (10)$$

$$BOT_{p/gc} = BLOAD_p * PLO_{gc} \quad (11)$$

$$BOT_{p/bc} = BLOAD_p * PLO_{bc} \quad (12)$$

where

p_{kp} = probability of kill per single PGM weapon

p_{kgb} = probability of kill per single gravity bomb

$BOT_{p/gc}$ = bombs on target for PGM in good CC

$BOT_{p/bc}$ = bombs on target for PGM in bad CC

BOT_{gb} = bombs on target for gravity bomb given visibility of the target

$BLOAD_p$ = pgm bomb load per sortie

PLO_{gc} = probability of PGM lock-on in good CC (derived from EOTDA simulation and scenario standoff range)

PLO_{bc} = probability of PGM lock-on in bad CC (derived from EOTDA simulation and scenario standoff range)

$PCFLOS_{p/gc}$ = probability of CFLOS for PGM in good CC

$PCFLOS_{p/bc}$ = probability of CFLOS for PGM in bad CC

$PCFLOS_{gb/gc}$ = probability of CFLOS for gravity bomb in good CC

$PCFLOS_{gb/bc}$ = probability of CFLOS for gravity bomb in bad CC

$p_{gc/gcf}$ = probability of good CC given good forecast

$$\approx 1-\frac{\sigma_{cc}}{C_{cc}}+\frac{\sigma_{cc}^2}{2C_{cc}^2};C_{cc}=3/8 \quad (13)$$

σ_{cc} = standard deviation of CC forecast error

$p_{bc/gcf}$ = probability of bad CC given good forecast

$$= 1-p_{gc/gcf} \quad (14)$$

$p_{bc/bcf}$ = probability of bad CC given bad forecast

$$\approx 1-\frac{\sigma_{cc}}{\left(1-C_{cc}\right)}+\frac{\sigma_{cc}^2}{2\left(1-C_{cc}\right)^2} \quad (15)$$

$p_{gc/bcf}$ = probability of good CC given bad forecast

$$= 1-p_{bc/bcf} \quad (16)$$

p_{gcf} = probability of good CC forecast

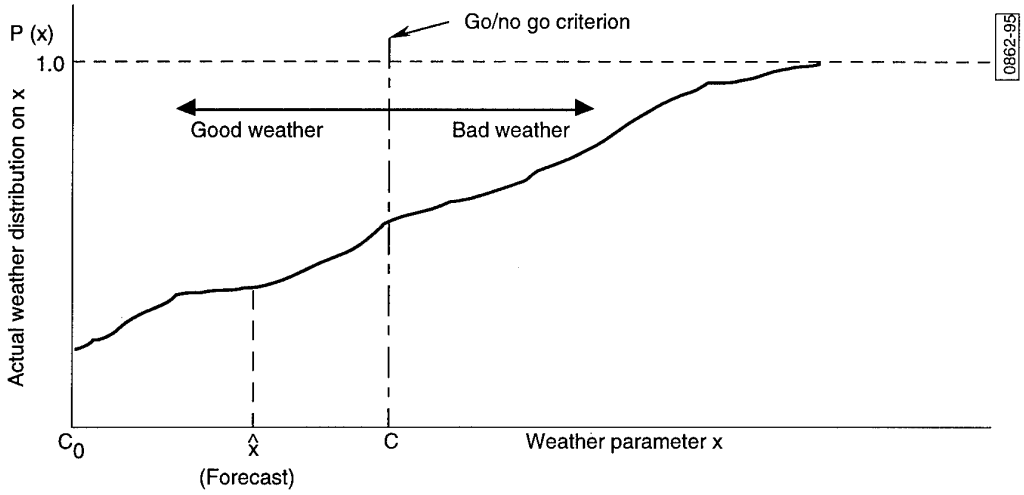
p_{bcf} = probability of bad CC forecast

The FORUM described above can be summarized by Figure 8, wherein the weather forecast accuracy, mission CONOPs usage of weather data, weapon effectiveness, and actual weather conditions all affect the mission MOEs: sorties expended and days elapsed to mission success.

MULTITARGET EXTENSIONS AND FORCE MULTIPLICATION

The FORUM described above is for a single target. It is desirable to look at multitarget/multisortie scenarios, because a real payoff in resource saving via forecast usage is the force multiplication effect in a theater campaign environment. Over a large theater area covered by many potential targets of varying value, the theater commander would like to place his resources where they are most effective in a target value sense.

For example, if some high value targets repeatedly are made inaccessible to attack due to weather conditions, the commander would like to allocate resources on those days to lesser value



$$p_{g/g} = [\int_{C_0}^{C} P_\varepsilon (C-x)p(x)dx]/[\int_{C_0}^{C} P(x)dx]$$

$p_{g/g}$ = probability of good weather given a good weather forecast

$p(x)$ = density function of actual weather parameter x

$P\varepsilon(*)$ = distribution function of weather parameter $\hat{x}$ measurement forecast error

Figure 7. Weather parameter accuracy effect on forecasts.

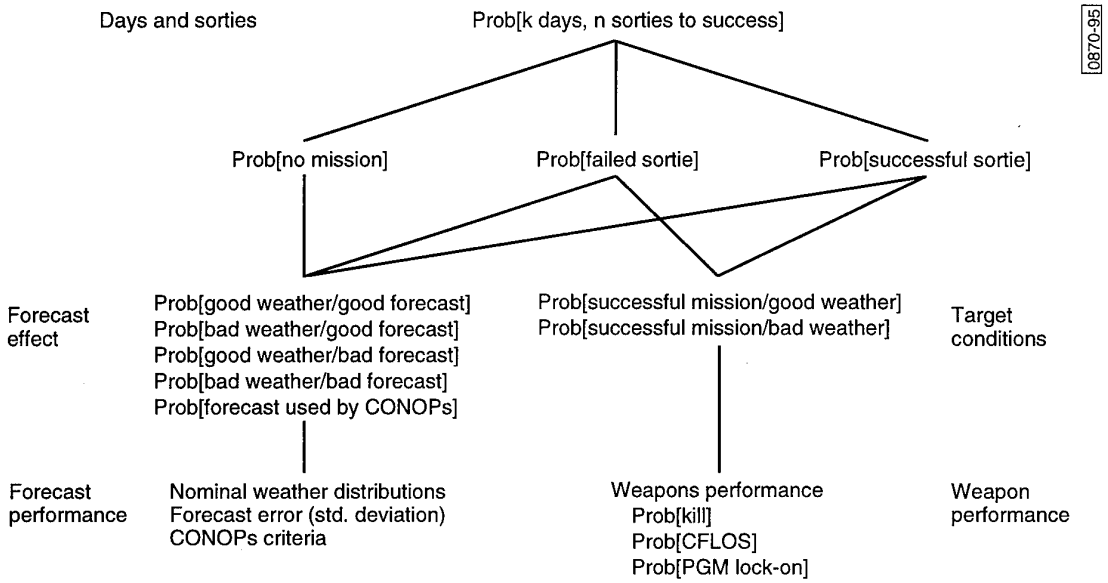
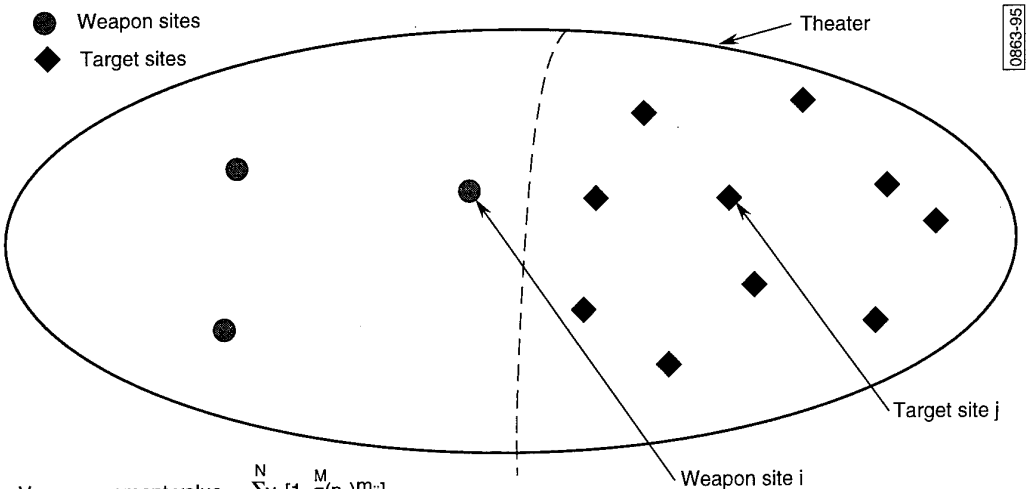


Figure 8. FORUM single target model flow.



V = engagement value = $\sum_{j}^{N} v_j [1 - \pi_{1}^{M} (p_{ij})^{m_{ij}}]$

p_{ij} = probability of unsuccessful attack by weapon site i on target site j

V_j = value of target site j

m_{ij} = number of weapon i sorties on target j

N = number of target sites

M = number of weapon sites

$p_{ij} = [1 - a_{ij} P_{ij}]$

P_{ij} = probability of successful weapon i attack on target j

a_{ij} = accessibility of site i to j

$\sum_{j} m_{ij} < n_i$

n_i = number of weapons at site i

Figure 9. Day k of campaign theater model.

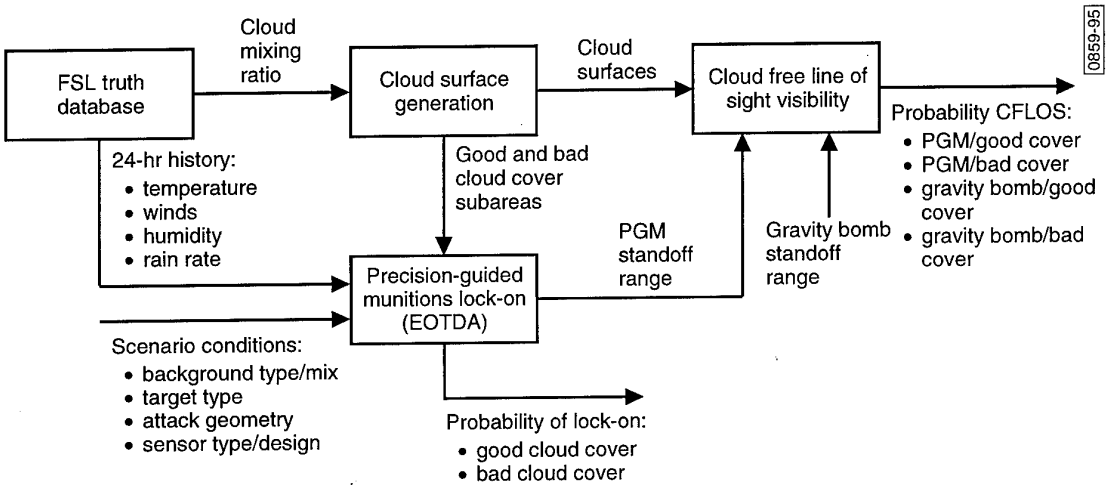


Figure 10. Weapon visibility and delivery analyses.

accessible targets so that each day the commander is able to allocate resources in an expected high rate of return fashion. This allows him to cover more targets with the same resources, or it reduces the forces needed to cover a fixed set of targets.

Let us formulate this problem as depicted in Figure 9. The number of sorties sent by the commander on any given day is a function of target value, number of sorties available, accessibility of weapon sites to the targets, and probability of success per assignment. This last parameter is influenced not only by the weapon effectiveness but also by the effects of weather and weather prediction on the CONOPs in effect. As we saw in the single target case described above, this probability can be related to these effects by a probabilistic model that incorporates the CONOPs decision criteria, weather forecast accuracy, type of weather expected, and weapon ability to act in good and bad weather.

By simulating this problem in Monte Carlo fashion for a representative command assignment algorithm, one can highlight the force multiplication advantages of weather forecast usage. Expected mission MOEs would be targets killed, target value killed, resources expended, and elapsed days to mission completion. Resources expended, in particular, will highlight the force multiplicative benefits of weather forecasts and sensitivity to forecast accuracy. Note also, that the Monte Carlo formulation does not require the assumption of day-to-day independence of event probabilities, since any correlation can be explicitly modeled in the pseudo-random draw processes.

The choice of weapon sorties on targets m_{ij} is made sequentially starting with the most valuable surviving target on any given day and working toward the least valuable survivor until all sortie resources are expended. The probability of no sortie on a given target due to bad weather is drawn from probability p_1 of Equation 2, and this target is removed from the targeting list on that day. Then P_{ij} of Figure 9 is taken to be the same as p_3 of Equation 4 for each weapon/target pairing (i, j) in the scenario when the weapon assignments are made. The actual target kill probability is drawn from Equations 10–16 as actual weather conditions are drawn per target site.

CLOUDS AND WEAPON VISIBILITY

The remaining portions of the analysis effort are mission specific in that they deal with CFLOS visibility (Ref. 8) and PGM performance at the target site (Ref. 9). Figure 10 shows an overview of the principle analysis tasks associated with generating the probabilities of CFLOS and PGM lock-on in Equations 10–12. The analyses that generate these probabilities are interconnected as shown in Figure 10. Of interest are the actual weather conditions to be experienced by the weapon system over the target area. Thus, the FSL truth database is accessed for these analyses. Of particular interest are subareas of the 140-by-140 horizontal grid within which local CC is good (i.e., cover < 3/8) and bad (i.e., cover > 3/8). To select these subareas, cloud surfaces must be generated from FSL CMR data using a threshold criterion of CMR > 0.0001 to define cells within which opaque clouds exist (Ref. 8).

Figure 11 shows a sample reconstruction of the cloud field over the study region at six hours after the beginning of forecast creation (i.e., 18 hours after midnight GMT). The analyst selects local regions where CC (i.e., average CFLOS visibility) is above and below the 3/8 criterion level. These are designated good and bad CC regions, and their location and extent are handed to the PGM analysis via EOTDA (Ref. 9).

The EOTDA simulation is a complex code that determines electro-optical sensor lock-on range as a function of target signature, background signature, weapon/target viewing geometry, and weapon sensor design. Target and background signatures start with a selection of types among a comprehensive list of alternatives. The signatures are calculated using a 24-hour history of temperature, humidity, wind, and precipitation data supplied by the FSL database. Detailed heat flow calculations determine temperature and signature levels at the end of this time. The weapon sensor design type and weapon/target viewing geometry then determine the target/background contrast level and the ranges at which the target can first be detected and then resolved against the background. The resolution range, which is generally shorter, is used as the lock-on range for the particular engagement under consideration. The user is faced with many complex alternatives in simulating a scenario. The approach taken here is to make those selections so that the conditions are representative of the full spectrum. When considering a target approach heading, it is assumed that the pilot can adapt to find a preferred approach angle for lock-on. The EOTDA then provides the nominal lock-on range for the good and bad weather subareas. The EOTDA is also used over a range of engagement conditions to determine probability of lock-on. The lock-on range under each condition is passed to an analysis of CFLOS visibility as shown in Figure 10.

CFLOS analysis uses a ray tracing approach to determine the probability of CFLOS at any given point on the grid. Figure 12 shows a typical ray-trace locus of points for many azimuths and ground ranges emanating from a single viewing point. Rays are traced from potential aircraft locations to all ground level grid points within a specified range. If any ray starts its path in a cloud or intersects a cloud, it is considered to be a non-visible ray. All visible rays divided by the total rays yields the probability of CFLOS at the viewing point. Such analyses are conducted in the good and bad CC subareas for weapon ranges of PGM and gravity bomb weapons to produce the probabilities of Equation 10. The PGM range limit comes from the EOTDA analysis. The gravity bomb value is taken from Figure 13, which shows the standoff range versus drop altitude for varying aircraft speeds. This figure was generated using a simple free-fall Newtonian gravity model without atmospheric drag consideration. The nominal aircraft speed is 500 km/hr (~ 330 mph) and the drop altitude is 3 km (~ 10,000 ft), which results in a standoff range of 3 km.

Figure 14 summarizes the scenario concept and analysis steps that model it. Both truth and forecast weather parameter databases are generated by FSL using calibrated ground measurements and a simulation of satellite-generated measurements to initiate the forecast path. These databases are used by Aerospace to:

- statistically characterize forecast accuracy
- develop CFLOS probabilities
- initiate thermal analysis of PGM weapon electro-optical sensors

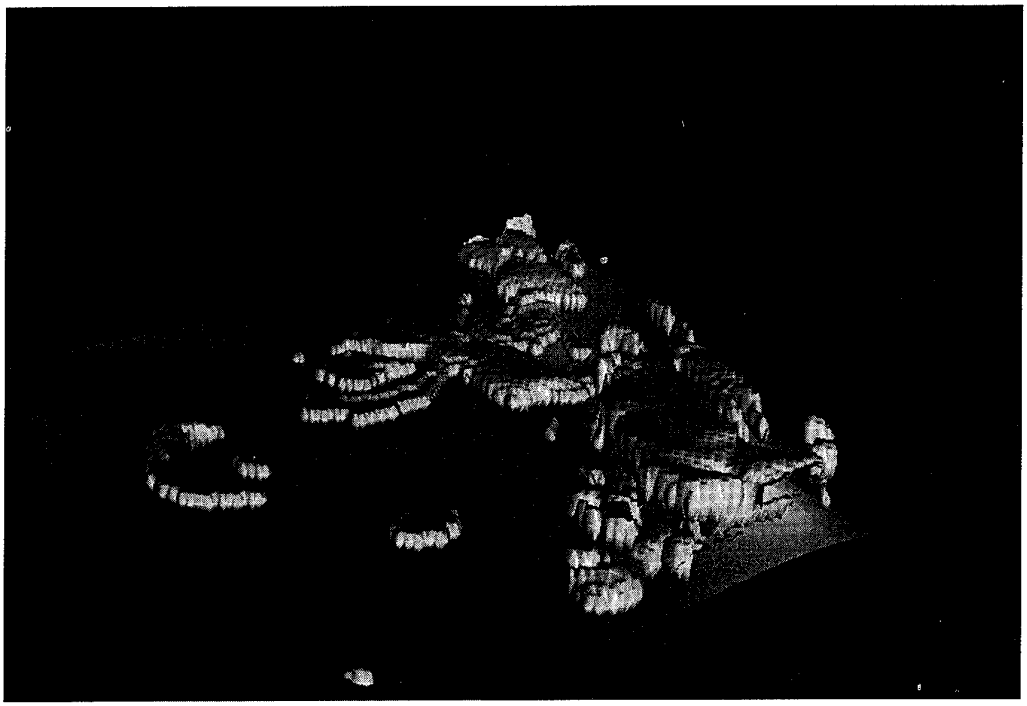


Figure 11. Cloud cover over the central United States (vertical scale exaggerated).

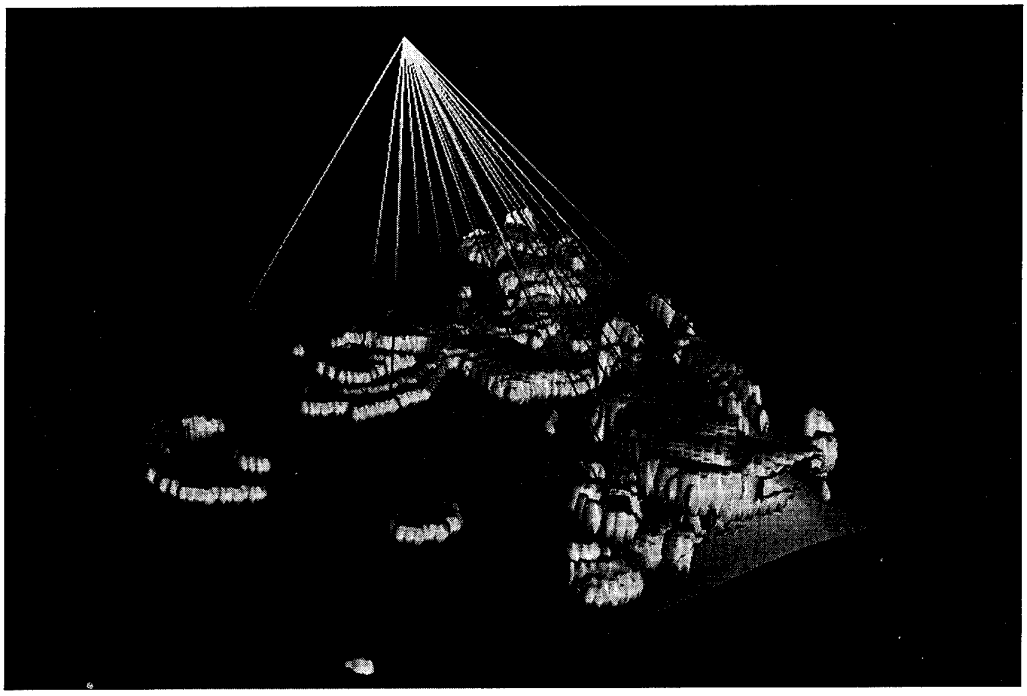


Figure 12. Aircraft-to-ground visibility via ray tracing (vertical scale exaggerated).

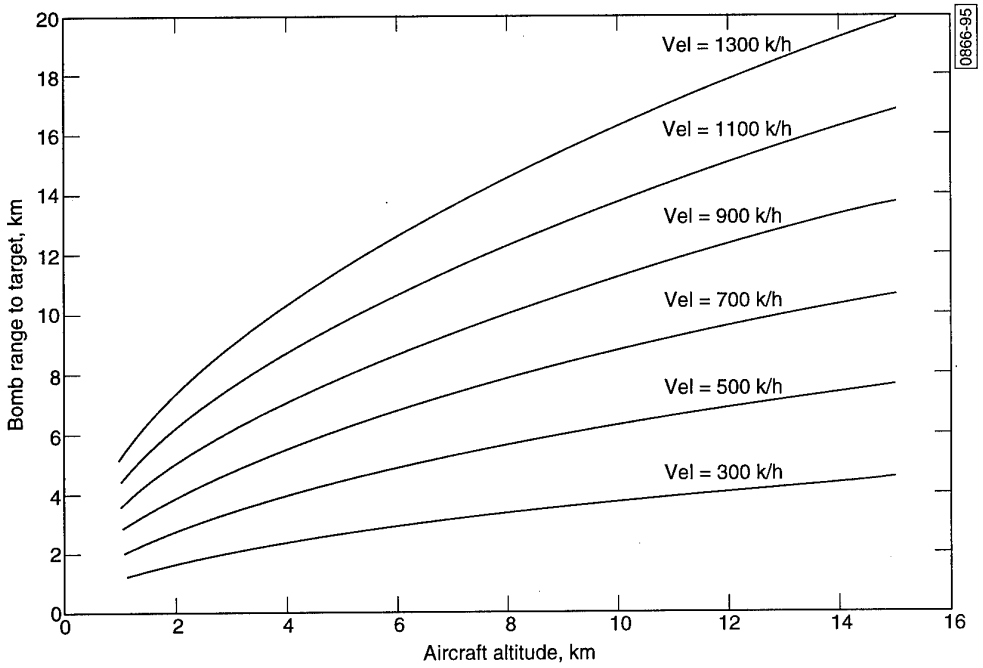


Figure 13. Gravity bomb range vs. altitude and aircraft speed.

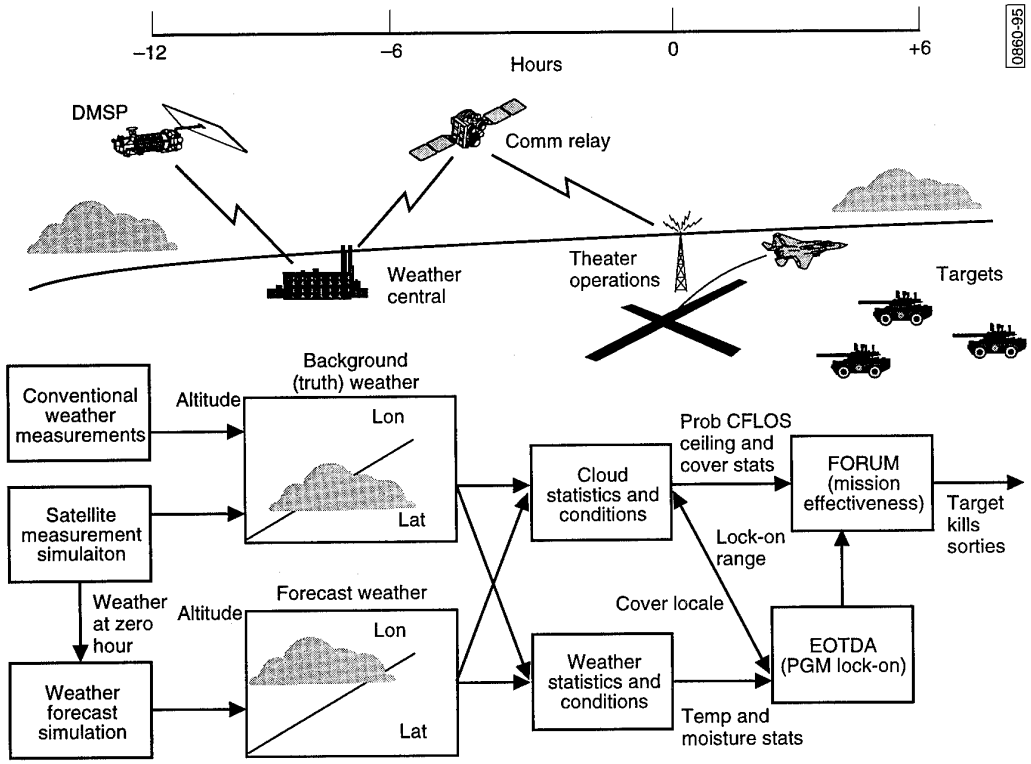


Figure 14. Weather forecast utility to the air-dropped munitions mission.

Table 1. FORUM Input Baseline

Parameter	Description	Units	Value
C_{cht}	Critical CH for mission go/no-go	km	Var (∞)
σ_{cht}	CH forecast uncertainty	km	Var (0)
C_{cc}	Critical CC for weapon load decision	–	3/8
σ_{cc}	CC forecast uncertainty	–	Var (0)
p_f	Probability forecast is used by mission command	–	1.0
p_{kp}	Probability of single precision-guided bomb kill	–	0.4
p_{kgb}	Probability of single gravity bomb kill	–	0.08
PLO_{gc}	Probability of PGM lock-on given good CC and CFLOS	–	1
$PCFLOS_{p/gc}$	Probability of PGM CFLOS given good CC	–	1
PLO_{bc}	Probability of PGM lock-on given bad CC and CFLOS	–	1
$PCFLOS_{p/bc}$	Probability of PGM CFLOS given bad CC	–	0
$PCFLOS_{gb/gc}$	Probability of gravity bomb CFLOS given good CC	–	1
$PCFLOS_{gb/bc}$	Probability of gravity bomb CFLOS given bad CC	–	4/8
mxmcdays	Maximum Monte Carlo days per scenario engagement	days	20
mctrgst	Number of target sites per Monte Carlo engagement	target sites	10
mcwpnst	Number of weapon sites per Monte Carlo engagement	weapon sites	1
mxsortie_wpnst	Maximum sorties per weapon site per day	sorties	5
$BLOAD_p$	Maximum PGM bomb load per sortie	bombs	5
BOT_{gb}	Maximum gravity bombs per sortie	bombs	5
ceilhtmn (ceilhtmx)	Minimum (maximum) CH for weather distribution	km	0 (10)
covermn (covermx)	Minimum (maximum) CC for weather distribution	–	0 (1)

These analyses in turn feed the FORUM input process, which evaluates resources used and time required to complete an air-dropped munitions mission.

PARAMETRIC ANALYSIS RESULTS AND IMPLICATIONS

As a means of gaining insight to the process and an understanding of its significance, a baseline case and sensitivity analysis were conducted using this model. In what follows, current best data values were used and, in some cases, the results are parameterized over a range of possible values in order to demonstrate sensitivity of the MOEs to principle performance parameters. Table 1 shows the baseline values assumed for this study. The first column contains the parameter symbol, the second a brief description, units in the third, and value in the fourth. Where a Var notation appears, this parameter takes on varying value for the sensitivities analyses and a baseline value as shown in parentheses (i.e., the value when this parameter is not varied).

The scenario considered is that of ten separate target sites to be accessed by a single weapon site with up to five sorties per day allowed. The dimensions of the problem in terms of target and weapon sites and sortie resources could be expanded, but were kept small for purposes of exploration. The go/no-go CH threshold was varied to allow varying probability of being above the threshold with a fixed distribution of CH values. The forecast uncertainty on CH and CC were also allowed to vary in order to view MOE sensitivity to these forecast accuracy parameters.

The first study varied the CH threshold or, equivalently, the probability of any target site being above the threshold and CH forecast accuracy. Of particular interest is the number of sorties flown per target kills as shown by Figure 15. The weapon delivery and kill assumptions that allow near-perfect kill conditions when a mission is launched provide for just above one sortie per target kill when the CH forecast accuracy is perfect (i.e., $\sigma_{cht} = 0$). As this uncertainty increases up to a maximum of $\sigma_{cht} = 4$ km, increased sorties are required per kill to account for failed missions when the CH is less than expected at the target site. The sorties also increase with decreasing probability of having a CH above the threshold, because this type of mission failure occurs more frequently. The dotted line represents the case in which weather CH forecast information is not used by the mission planner (i.e., sorties are flown as available against the targets without knowledge of the CH conditions over the target sites). As might be expected, this policy approaches the forecast performance as the probability of good CH weather increases. When CH conditions are poor (i.e., probability of good CH < 0.5) the policy without forecast results in more than twice the sorties as the policy using perfect CH forecast information. This is another way of saying that weather forecasts are most valuable in poor weather conditions (i.e., tropical versus desert environments).

If one were to consider setting a requirement on CH forecast accuracy, the breakpoint for using a forecast policy and no forecast might be around the nominal probability of good CH at 0.75 or less. This represents a level of ideal conditions found in the Desert Storm experience (Ref. 5). For weather conditions above this level, forecast policy would do no better than a no-forecast dispatch policy if the CH forecast accuracy were $\sigma_{cht} \geq 2$ km. This would be a required level of CH forecast accuracy to reap the benefits of forecast assignment in scenarios involving consistently low CH conditions.

Now consider the effect of CC forecast accuracy on mission performance. This parameter influences the decision as to whether PGMs or gravity bombs are to be loaded per sortie. Since weapon effectiveness in good and bad CC conditions are wrapped in that sensitivity, the number of sorties flown is not as strongly influenced by forecast accuracy if the weapons have similar kill effectiveness (i.e., the loading decision is not critical if weapon effectiveness is the same with either decision).

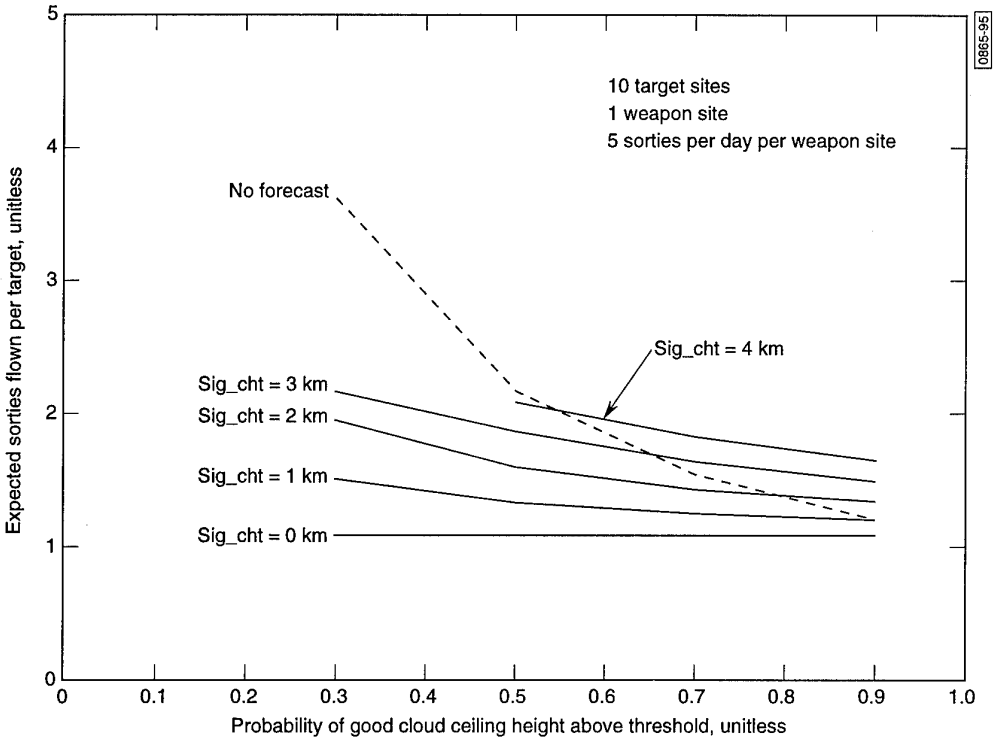


Figure 15. Expected sorties vs. the probability of good cloud ceiling height and cloud ceiling height forecast uncertainty.

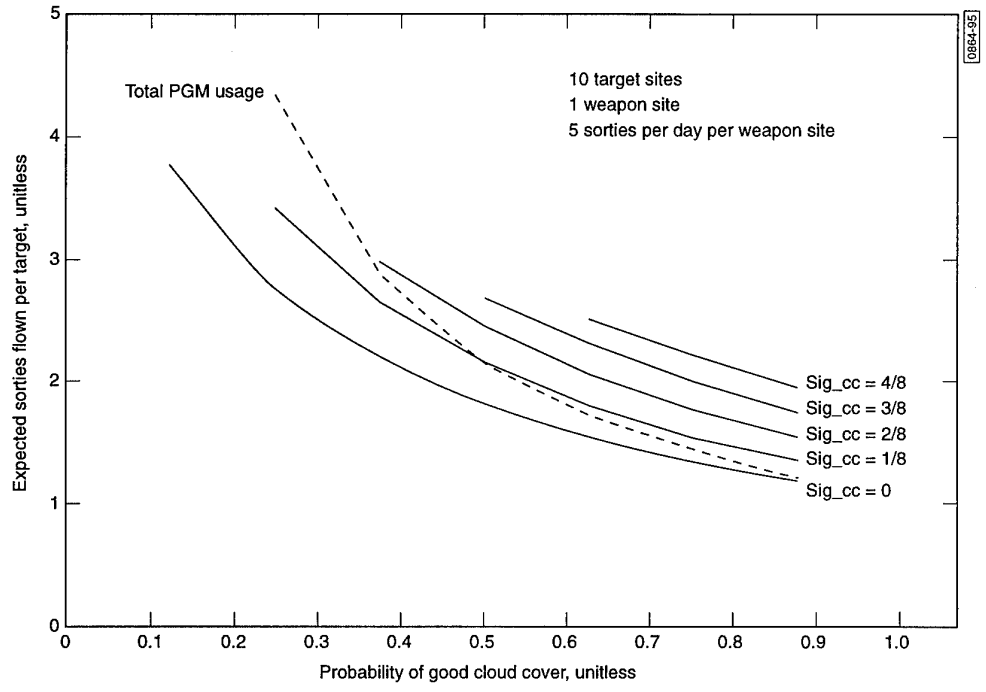


Figure 16. Sorties vs. the probability of good cloud cover and cloud cover forecast uncertainty.

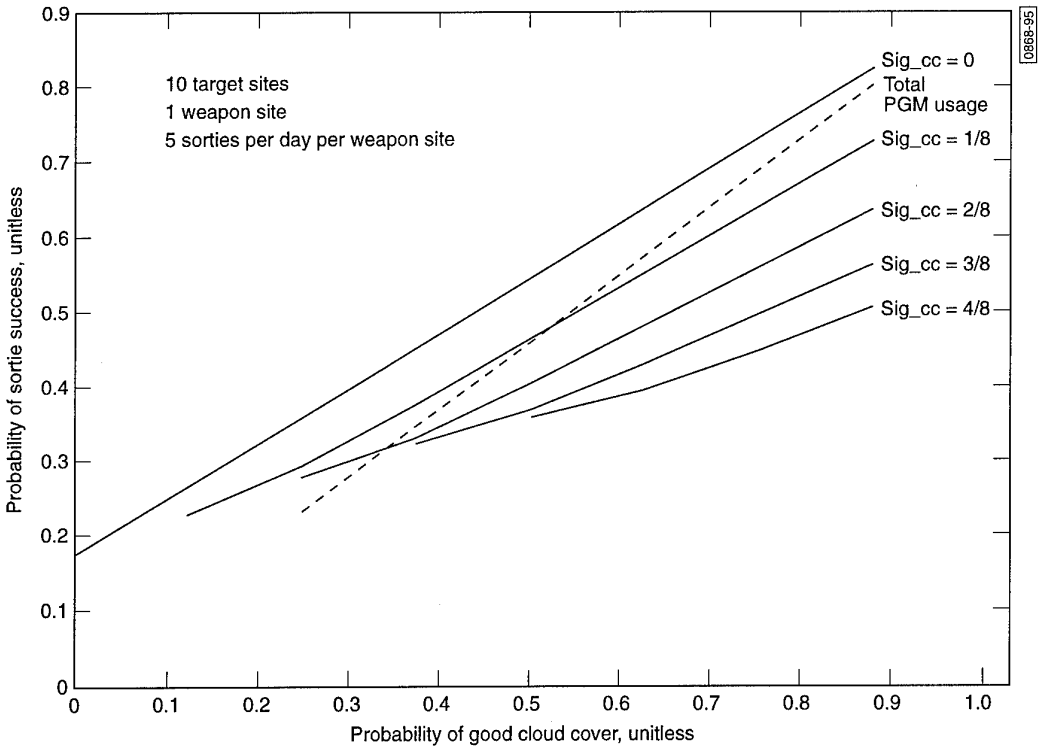


Figure 17. Probability of sortie success vs. the probability of good cover and cloud cover forecast uncertainty.

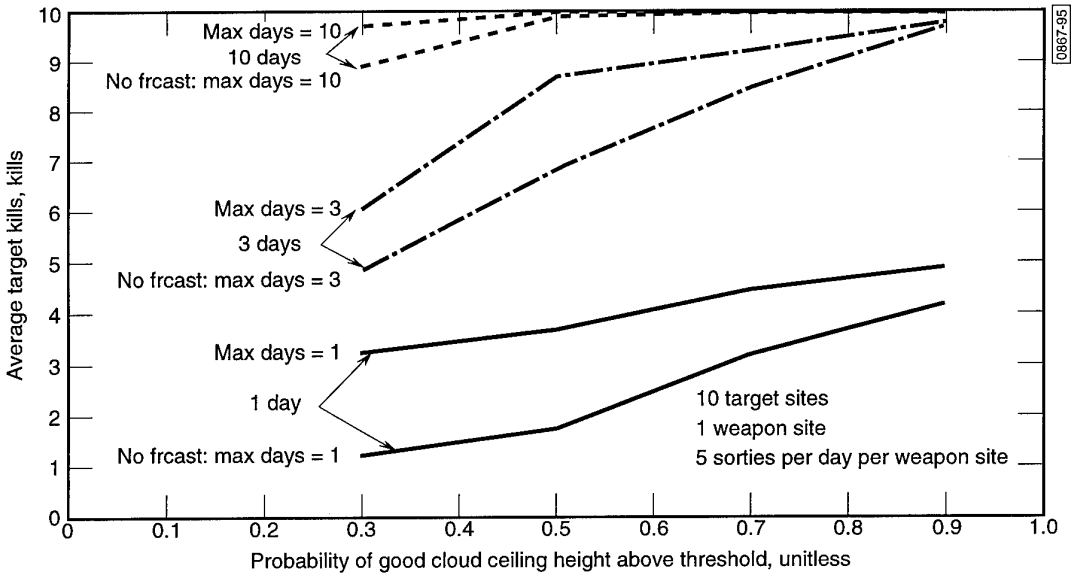


Figure 18. Average target kills vs. the probability of good cloud height ceiling and maximum days (compare perfect and no forecast).

Figure 16 shows the effect of actual CC probability and forecast accuracy on the number of sorties flown per target. Also shown by the dotted curve are the sorties flown versus CC probability when PGMs are used exclusively (i.e., every sortie is flown with PGMs).

Figure 16 shows that the loading decision decreases sorties flown over the PGM loading policy for probability of good CC $\leq$ 0.75 when the CC forecast uncertainty is $\sigma_{cc} \leq 1/16$. This suggests that a requirement on CC uncertainty might be set at the 1/16 (one sigma) level to assure benefits of the weapon loading decision in less than fair weather conditions. Another metric for viewing the influence of the weapon loading decision is depicted in Figure 17, which shows the probability of sortie success (i.e., target kill) versus the probability of good CC and CC forecast uncertainty. Here again, the policy of loading PGMs exclusively crosses the forecast-guided loading curves when the probability of good CC is 0.75 and CC forecast uncertainty is 1/16. These numbers are not important now since they are the result of preliminary analyses on limited case data. However, the procedures suggested for setting a requirement may be worthy of further expansion.

Another interesting MOE that reflects the force multiplicative advantage of forecast scheduling is shown in Figure 18. Here the number of target kills accomplished within a fixed number of days is plotted against the probability of good CH conditions. Pairs of curves are shown for maximum day limits of one, three, and ten days. Each pair of curves contains one using perfect forecast information (i.e., $\sigma_{cht} = 0$) and are without using weather forecast CH (i.e., sorties are scheduled against targets without consideration of mission abortion due to the target site CH). When the maximum time is limited to one or three days, there is considerable difference in target kill performance especially when the probability of good CH conditions is low. As the time allowed approaches ten days, the difference with and without forecast is less pronounced, because either way, the ten targets are eliminated by repeated attack over the extended time allowed.

SUMMARY AND CONCLUSIONS

The purpose of this paper is to describe an end-to-end analysis and modeling process that traces the value of weather forecast data to military missions. The procedures presented herein include:

- simulation of temporally and spatially-dependent weather parameters from calibrated ground sources for truth and satellite-simulated measurement for forecast
- statistical characterization of forecast weather parameter error in space and time
- use of weather parameter data to create cloud visibility and weapon sensor engagement performance probabilities for an air munitions drop mission
- use of nominal weather climatology, forecast accuracy, weapon system performance, CONOPs, and scenario conditions to evaluate mission MOEs and their sensitivities to these Measures of Performance (MOPs)
- exploration of MOE/MOP sensitivities to set requirements on MOP values

The numerical results set forth here are preliminary in that specific mission, weather databases, weapon systems, and CONOPs are employed. The procedures, however, have broader application potential. These techniques can be refined and extended to a broad variety of military and civilian missions. Only minor modification is needed to address differing systems and CONOPs.

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MULTIPLE HYPOTHESIS TRACKING vs KALMAN FILTER WITH NEAREST NEIGHBOR CORRELATION. PERFORMANCE COMPARISON.

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Summary
Multi-target tracking systems in operational use today generally adopt standard Kalman filter techniques, coupled with a maneuver detector to introduce some kind of adaptivity, and nearest neighbor (NN) correlation with a plethora of heuristics to improve the performance of the system. Through Monte Carlo simulations, the performance of a multiple hypothesis multi-target tracking algorithm were evaluated in terms of the probability of correct association of a track to a target. The performance of a Kalman filter plus NN is used as reference. Results are presented for a number of study cases related to several operational situations of interest (e.g. up to eight targets undergoing maneuvers). A preliminary evaluation of the processing time ensures that the MHT algorithm can be implemented in modern computers having adequate processing power.

1. Introduction

Multi-target tracking systems in operational use today generally adopt standard Kalman filter techniques, coupled with a maneuver detector to introduce some kind of adaptivity, and nearest neighbor correlation with a plethora of heuristics to improve the performance of the system [1,2]. Limitations of such an approach are analyzed in [3] and can be summarised in the limited performance in presence of spurious measurements and in the unavoidable compromise between two contrasting requirements, i.e. good filtering of measurement noise and promptness in following sharp maneuvers. The necessity of ensuring track continuity under critical conditions, like rapidly maneuvering targets in presence of natural and/or intentional disturbances in high target density scenarios, requires more sophisticated correlation and association algorithms. They are JPDA (Joint Probabilistic Data Association) [4] and MHT (Multiple Hypothesis Tracking) [5,6] which in the recent past were considered unaffordable because of their high computational and memory requirements. Now they can be reconsidered in view of the continuous advances in computer technology (like powerful workstations and parallel computers). These algorithms, combined with a multiple model approach, where several dynamic models are postulated for the target, represent viable and effective solutions to the problem. MHT specifically is recognized as the theoretically best approach to the multi-target tracking problem. It includes the implementation of a multi-scan correlation algorithm which delays decision on the association of plots to targets so as to exploit subsequent information. It also offers the possibility of trading-off computational requirements with algorithm performance. [5] is a pioneering work on multiple hypothesis tracking. Other sub-optimal implementations can be found in [6] to [9].
The purpose of this paper is to provide a comparison between traditional tracking algorithms and a sub-optimal implementation of the MHT algorithm in terms of track maintenance capability, i.e. the probability of not loosing or not switching tracks.
This paper is organized as follows. Section 2 provides a brief description of the MHT theory. In section 3 the software details of our sub-optimal implementation are described. Simulation results relative to specific study cases are presented and analyzed in section 4. Finally, section 5 gives a feeling of the computational requirements of the algorithm and hints on future work.

2.The MHT algorithm

MHT is recognized as the theoretically best approach to the multi-target tracking problem, yet it requires a considerable amount of computation and memory resources. A practical MHT implementation can be obtained by limiting the depth of the multi-scan correlation and by adopting several other techniques which limit processing requirements. In the sub-optimal implementation of the MHT described here we have followed the track oriented approach [8], which is more flexible and efficient and also intuitively more appealing than the measurement oriented approach [5]. In the track oriented approach, each target can be depicted (see figure 1) as a tree, where the root of the tree represents the birth of the target, and the branches represent different track hypotheses for the target. At each scan, new branches are formed corresponding to the different dynamic models for the target (constant velocity or maneuver model) [10]. Then each branch is further expanded to account for feasible associations with the plots in the scan or a missed detection. A trace of successive branches from the root to a leaf of the tree corresponds to a potential track (hypothesis) for the target. A likelihood value, measuring how well the sequence of reports matches the hypothesis, can be computed for each potential track. A global hypothesis (see figure 1) is formed by combining tracks from

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different target trees picking at most one track from each target tree. Assuming one return, at most, per target per scan, then tracks forming a feasible global hypothesis should not share the same returns.

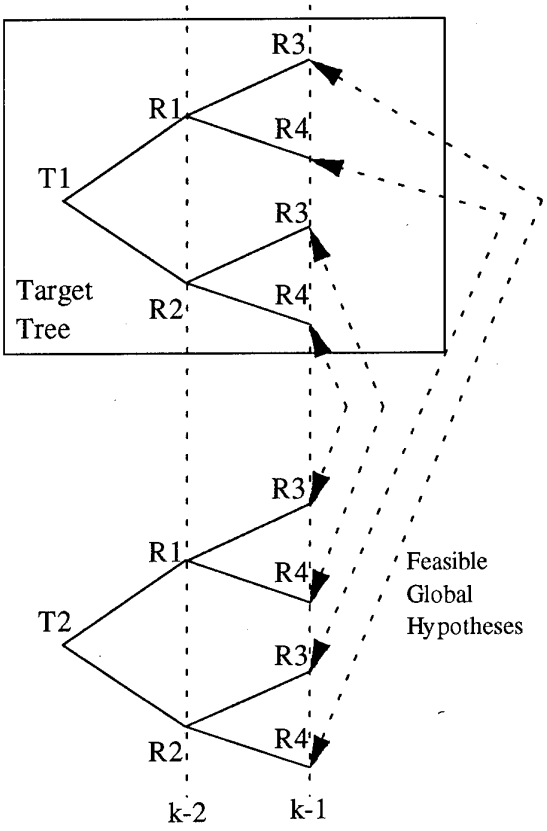


Figure 1. Feasible global hypotheses from two trees related to targets T1 and T2 and built with plots Ri.

Likelihoods of the global hypotheses are then evaluated from the likelihoods of the tracks (see ensuing Section 2.1). The global hypothesis with the highest likelihood is selected and used to identify the most likely set of branches for each target N scans before the actual scan. The unlikely branches are pruned away (see figure 2). This retrospective procedure (N-scanback approximation) solves the multiple plot-to-target association problem. Compare now MHT with JPDA algorithm. JPDA can be considered as a zero-scan algorithm. It tends to coalesce closely spaced targets. It is not always easy to incorporate in the JPDA algorithm a priori information such as, for instance, the target identity. It has a relatively large computational requirement. In principle JPDA requires the calculation of the probability of all the global hypotheses; each probability is used to weigh the correlating plots that update the system track. On the contrary, MHT needs to determine only the most likely global hypothesis and this can be achieved without going through all the global hypotheses as JPDA does [8].

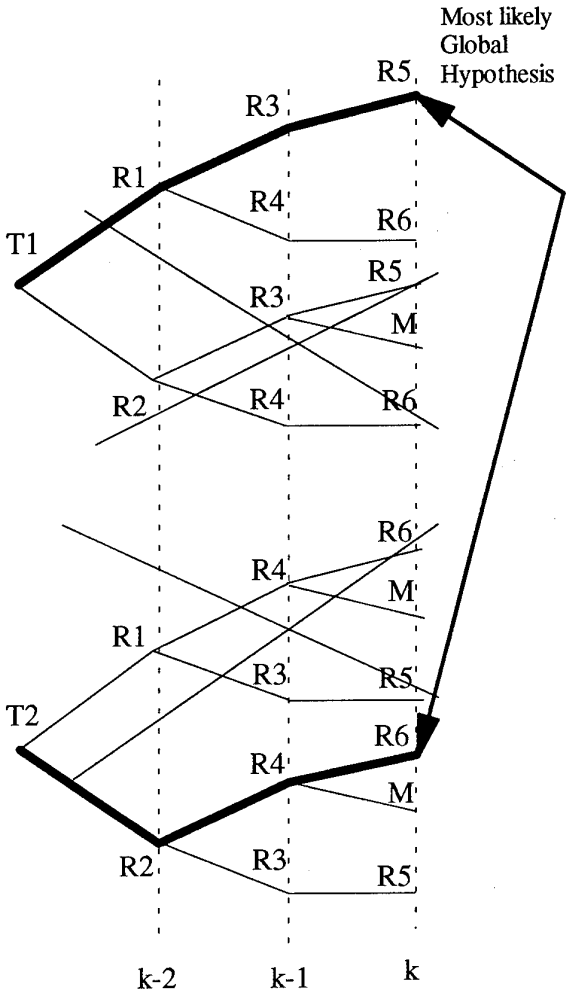


Figure 2. 2-scan approximation technique applied to target trees T1 and T2 (M stands for missed detection).

2.1 Evaluation of global hypothesis likelihood

The purpose of this section is to give the mathematical expression of the probability of the global hypothesis. Consider the following set of radar measurements:

$$Z^k = \left\{ Z^{k-1}, z(k) \right\}$$

where z(k) is the set of radar measurements at the k-th scan and Z^k is the set of radar measurements up to the k-th scan. Indicate with

$$q_i^k = \left\{ q_{l(i)}^{k-1}, q_i(k) \right\}$$

a set of hypotheses, where q_i^k is the i-th association hypothesis up to the k-th scan, $q_i(k)$ is the i-th hypothesis associating plots and targets at the k-th scan and $q_{l(i)}^{k-1}$ is the l-th association hypothesis up to the (k-1)-th scan from which the i-th association hypothesis derives. It can be shown [8,11] that the following equation applies:

$$P\left(q_i(k)|Z^k\right)=$$
$$=\overline{C}^{-1}\cdot P\left(q_{I(i)}^{k-1}|Z^{k-1}\right)\cdot\left\{P_\chi^\chi\right\}\cdot$$
$$\cdot\left\{\left[\left(1-P_\chi\right)\cdot\left(1-P_d\right)\cdot\left(1-P_m\right)\right]^{\tau-\chi-d}\right\}\cdot$$
$$\cdot\left\{\prod_{t\in T_m}\left[\frac{\left(1-P_\chi\right)\cdot P_d\cdot P_m}{\lambda_{fa}}\right]\cdot\left[\frac{p_{tm}\left(Z_t(k)|q_i^k\right)}{p_{fa}\left(Z_t(k)|q_i^k\right)}\right]\right\}\cdot$$
$$\cdot\left\{\prod_{t\in T_{d-m}}\left[\frac{\left(1-P_\chi\right)\cdot P_d\cdot\left(1-P_m\right)}{\lambda_{fa}}\right]\cdot\left[\frac{p_{ts}\left(Z_t(k)|q_i^k\right)}{p_{fa}\left(Z_t(k)|q_i^k\right)}\right]\right\}\cdot$$
$$\cdot\left\{\prod_{t\in T_b}\left[\frac{\lambda_b}{\lambda_{fa}}\right]\cdot\left[\frac{p_b\left(Z_t(k)|q_i^k\right)}{p_{fa}\left(Z_t(k)|q_i^k\right)}\right]\right\}$$

where:

$\overline{C}$ is a constant:

$$\overline{C}^{-1}=C^{-1}\cdot\left\{\frac{e^{-(\lambda_b+\lambda_{fa})}}{r!}\cdot\lambda_{fa}^r\cdot\left[p_{fa}\left(Z_t(k)|q_i^k\right)\right]^r\right\}$$

and

τ=number of postulated targets;
r=number of plots received at the current scan;
χ=number of terminated targets;
d=number of detected targets from (τ–χ) non-terminated targets;
m=number of maneuvering targets;
b=number of born targets;
P_χ = probability of target termination;
P_d = probability of target detection;
P_m = probability of maneuvering target;
λ_{fa} = expected number of false alarms in one scan;
λ_b = expected number of born targets in one scan;
p_{tm} ( ) = conditional likelihood that the received plots are originated from a maneuvering target;
p_{ts} ( ) = conditional likelihood that the received plots are originated from a non-maneuvering target;
p_b ( ) = conditional likelihood that the received plots are originated from born targets;
p_{fa} ( ) = conditional likelihood that the received plots are originated from false alarms;
T_m = set of plots associated with maneuvering and detected targets;
T_{d-m} = set of plots associated with non-maneuvering and detected targets;
T_b = set of plots associated with born targets.

The previous equation, which is recursive in nature, updates the global hypothesis likelihood by the product of five terms which correspond to five independent events. These events are respectively related to terminating targets, non detected targets, maneuvering targets, non maneuvering targets and, finally, born targets. The false alarm event is represented in the last three events and in the constant term via the quantities λ_{fa} and p_{fa} ( ). The equation above determines the most likely global hypothesis which is selected to update the system tracks.

2.2 Hypothesis reduction techniques

Techniques have been devised to reduce the number of hypotheses to a manageable level. They are as follows.
gating: it is performed to reduce the number of plots which correlate with the track. This is implemented, as usual, by calculating the distance (also referred to as statistical innovation) between plot and predicted position of track and comparing the distance with a threshold via a proper metric. More precisely, three gates are built around the predicted position of the track; the inner two ones serve the purpose of detecting, with variable degree of confidence, a target maneuver, while the outermost gate limits the region to be searched for the plots originated from a maneuvering target.
track hypothesis updating: maneuver branches are created only if a maneuver is detected: a maneuver is modeled as a random process by increasing the prediction error covariance matrix (see, for details,[1] Section 4.3.1). A missed detection hypothesis is formulated when the following events occur: no plot falls inside the two inner gates or plot falls inside the two inner correlation gates but it correlates with more than one track.
clustering: tracks are grouped in clusters, each including only tracks which compete in the assignment process. This transforms the original assignment problem into several uncoupled problems of lower size, thus limiting the exponential growth in number of the global hypotheses.
N-scanback approximation: it limits the depth of the multi-scan correlation (see Section 2 and figure 2).
tree pruning: it limits the number of track hypotheses per target tree to the M most likely.

The gate sizes, together with N and M, i.e. the values of the scanback and tree pruning parameters, are examples of user definable parameters which can be selected to control the trade-off between performance and computation requirements.

3.Description of tracking testbed

The purpose of this section is to describe the flow-chart of the implemented software, the choice of data structures managed by the program and of the software language, and the graphical facilities provided by the testbed.

3.1 Flow-chart

A flow-chart of the implemented software is shown in figure 3.

Block 1 It performs conventional processing functions (gating and maneuver detection) that are typical of tracking algorithms.
Block 2 New track hypotheses (i.e. the branches of a target tree) are formed on the basis of the new correlating plots.
Block 3 The track likelihood is calculated according to the equation introduced in Section 2.1.
Block 4 It limits the maximum number of branches per tree.
Block 5 When a missed detection hypothesis is formulated (see Section 2.2, track hypothesis updating), a new branch is generated in the target tree.
Block 6 The clustering function is implemented as described in Section 2.2.
Block 7 The most likely global hypothesis is extracted with an *ad hoc* algorithm that avoids the screening of all the feasible global hypotheses; all branches which do not pertain to the selected global hypothesis are pruned as shown in figure 2.
Block 8 The Kalman filter algorithm is recursively applied to all the tracks that survived after the pruning. See track hypotheses represented with bold and light lines in figure 2.

The software design exploits the representation of track hypotheses and plot-track correlation via logical trees and branches, respectively. Thus the multi-scan correlation problem is coded in the software by operating on tree data structures. The software has been written in C. The C language has been chosen for its efficient handling of complex data structures, dynamic storage allocation and recursion (e.g. manipulation of tree structures). The software resulted in a few thousand lines of code. The testbed is implemented on a SUN Sparc 2 workstation.

3.2 The interface

A very attractive feature of the testbed is the graphical interface which has proven very useful to analyze and gain insight into the problem. This interface is implemented using the X-Window library. Buttons make it possible to control the progress of the simulation on a scan-by-scan basis, and select data to be displayed. The interface also allows an easy build-up of scenarios to be tested; it provides the output of results and statistics in a graphical form. A snapshot of the display is provided in fig. 4. The display shows 38 buttons corresponding to many functions that can be activated with the mouse. For instance, the button *Temp* corresponds to a processing mode that visualizes how the tracks evolve in a scan-to-scan fashion. The most likely track hypotheses and all the other tentative hypotheses are depicted together with the ellipsoidal correlation gates. Figure 5 is an example of the target speed vs time; there are two curves, one corresponds to the true target speed while the other, lagging behind, refers to the target speed estimated by the MHT tracking filter.

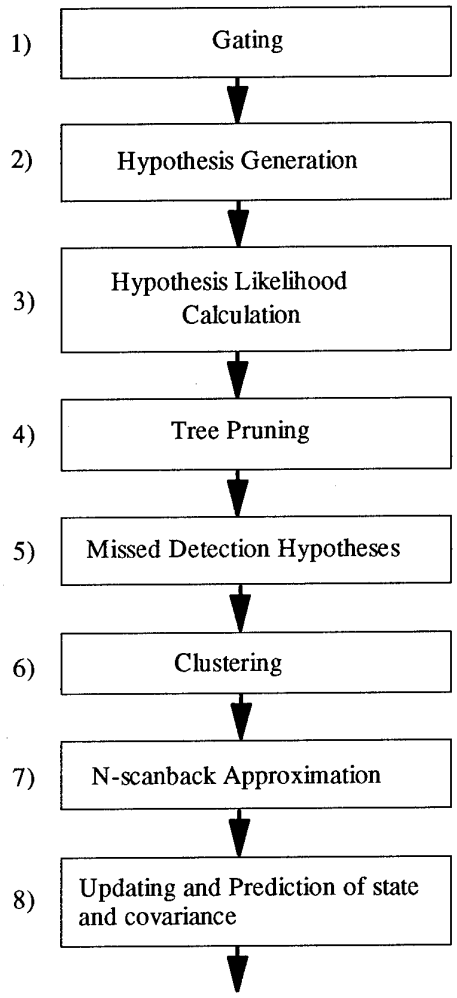


Figure 3. Flow-chart of the MHT algorithm.

4.Description of simulation results

The performance of the MHT multi-scan algorithm is compared with that of a traditional zero-scan Kalman filter which updates the track with that plot having the minimum statistical distance (i.e. NN logic) from the track predicted position. Association ambiguities are resolved by making the best overall selection of plot-track pairings. The target state vector comprises position and velocity along the x and y coordinate axes; process noises along the direction parallel and perpendicular to the speed are modeled as mutually independent, zero-mean, white Gaussian, random sequences and the ratio of their variances is 1:9. Both tracking filters (i.e. the MHT multi-scan and the NN zero-scan) are equipped with the same target maneuver detector and adaptation of tracking filter parameters (see, for details, [1] Section 4.3.1). The radar is always located in the origin of the Cartesian coordinate reference system and it provides range and azimuth measurements with standard deviation errors of 50 m and 3.4 mrad respectively. The radar scan rate is 2 s. Each plot is detected with a detection probability Pd which is a parameter of the tracking simulation trial.

A single plot is received when targets fall in the same radar resolution cell. Sometimes, false plots due to clutter are randomly generated within a certain sector. Results provide the probability of loosing/switching a track against the value of Pd for each of the algorithms under consideration. One thousand Monte Carlo runs have been executed for each experiment.

4.1 Purpose of the simulation

Purpose of the simulation is to analyze both quality scenarios (i.e. few highly maneuvering targets, flying in sectors with heavy clutter, whose trajectories have been chosen so as to highlight specific performance and behaviours of the tracking system) and also a dense scenario where an average figure of performance is extracted. The following subsections describe in details for each scenario the achieved performance results.

4.2 Two crossing targets

The simplest problem which can be considered in multi-target tracking is depicted in Fig. 6a. Two targets fly along intersecting straight-line paths at a speed of 250 m/s. Paths intersect midway through the 50-scan flight duration forming an angle of 4.6 degrees. In this situation, the consequence of incorrect correlations is the so-called "track-switching" phenomenon. The probability of track switching is drawn in figure 6b versus the probability of detection Pd. For the classical tracking filter, the track switching probability increases as the Pd value reduces from 1 to 0.6, while it remains practically constant, at a lower value, for the multi-scan algorithms. In particular the 2-scan algorithm provides a significant performance improvement.

4.3 Two targets joining and diverging

In this scenario targets maneuver and separate rather than crossing. The kinematic characteristics of the target paths are the following. Targets start moving along two straight lines with components of velocity of 100 m/s on the x and y axes; subsequently targets perform a 90 degrees turn with maneuver acceleration of 3g. The minimum distance between the two tracks is approximately 200 m (see figure 7a). Figure 7b shows the achieved results in terms of the probability of track switching versus the value of Pd, for the three algorithms tested. The zero-scan algorithm implements a filter with a relatively slow reaction time. For this reason, as the targets converge and start maneuvering, targets tend to maintain their course and so the probability of crossing each other is very high. On the contrary multi-scan algorithms generate a maneuver hypothesis which follows the target maneuver with great promptness; thus, they are able to successfully resolve the scenario. This scenario is very tricky because targets separate with an angle identical to the one they form in the converging portion of the experiment. In fact, delaying the association decision for a few scans does not greatly reduce the association uncertainty. This explains why the 2-scan algorithm, coupled with a maneuver detector which does not estimate the acceleration, does not provide any increase in performance over the 1-scan algorithm when Pd=1. Of course, the performance rapidly deteriorates as the Pd value reduces from 1 to 0.6. For Pd values lower than 1, a few missed detections in the critical portion of the scenario would make it impossible, even for a well trained operator, to resolve the trajectories correctly.

4.4 Target in a looping maneuver

This scenario stresses the response of the filter in presence of a longitudinal maneuver. Actually it models (see figure 8a) a target performing a loop in the vertical plane. This maneuver is described, in the x-y plane, as a change of target velocity from +300 to -300 m/s with a longitudinal acceleration of -3g and with an additional change of target velocity from -300 to +300 m/s with a longitudinal acceleration of +3g. The corresponding probability of loosing the track is depicted in figure 8b. As usual, the MHT multi-scan algorithm provides a performance advantage over the classical zero-scan tracking algorithm for Pd values lower than 1.

4.5 Straight-line target in a clutter area

A target following a straight-line path (see figure 9a) at a rate of 300 m/s crosses a clutter bank of extension 3 km (along x) per 8 km (along y). The number of scans in which the target plot is within the clutter region is 5. A global number of 35 clutter plots are uniformly distributed within the above mentioned sector and this corresponds to a density of clutter plots of 1.5/km^2. The performance criterion is the probability of successfully traversing the clutter region. Such a capability, when compared with the poor performance of the NN algorithm, arises from the inclusion of knowledge of clutter maps in the equation evaluating the track likelihood (see Section 2.1). The probability of loosing the track is portrayed in Figure 9b. When Pd=1, miscorrelation occurs when a clutter plot falls closer to the track predicted position than the true plot originated by the target. This probability is very low with the current clutter density, and this explains why the track successfully traverses the clutter region with a very high probability when Pd=1. With lower values of the target detection probability Pd, the miscorrelation event has a higher probability; yet the hypotheses postulating a missed detection are not unlikely compared to all other hypotheses and this allows the MHT to bridge over spurious measurements and maintain the straight-line flight path.

4.6 Maneuvering target in clutter

This scenario investigates the capability of the tracking algorithm to follow a maneuvering target in clutter. Figure 10a shows the target which is moving on a

straight line path with components of velocity along both Cartesian axes, equal to 220 m/s. When the target enters a square clutter region of 6 by 6 km, it performs a turn of 180° with a centripetal acceleration of 5g. A number of 6 false plots are uniformly distributed in the clutter region corresponding to a density of clutter plots of 0.2/km^2. The probability of loosing the track is shown in figure 10b. As expected, the NN zero-scan algorithm shows a very reduced capability to follow the target in clutter. On the contrary, the multi-scan ensures a certain capability to track the target even though its performance is poor for low values of Pd.

4.7 Dense scenario

Figure 11a shows a dense scenario with eight targets: five targets move along straight line paths with velocity values in the order of 200 m/s; the remaining three targets undergo maneuvers with acceleration values between 3g and 5g. The duration of the acceleration is in the order of ten radar scans approximately. The interaction between at least two and up to four targets occurs a number of times during the temporal evolution of the operational scenario. Fig. 11a displays the temporal sequence of plots, pertinent to the eight targets, in the case of radar detection probability equal to one. The same figure shows the corresponding tracks (continuous lines) produced by the MHT algorithm with 1-scanback. To appreciate the performance comparison between the MHT and the NN zero-scan algorithm, figure 11b has been prepared. To limit the computational time, the MHT was set up to maintain just the best ten hypotheses per target tree and no significant performance loss was noticed. The numerical values depicted in the figure represent the summation of the lost and switched tracks in percentage. Indeed the MHT algorithm provides a useful service and the performance gain is more evident for low values of Pd. The greatest improvement is between the zero-scan and the 1-scan solutions. This experimental observation, together with the consideration that the processing requirements of the algorithm grow exponentially with the scanback parameter, suggests that at the moment the 1-scan algorithm has a greater performance to computational requirements ratio.

5.Concluding remarks

To give an idea of the computational time required by the MHT, a not optimized software implementation of the algorithm, running on a SUN SPARC 2 work station, gives the following figures: the computational time per scan (remind the number M of track hypotheses per target tree was set to 10) for the operational environment studied in section 4.7 is 40 ms. (0-scanback), 80 ms. (1-scanback) and 160 ms. (2-scanback). Thus the algorithm could process in real time, say, 200 targets flying in clusters, each cluster containing up to four targets, working with the 2-scanback strategy and a radar scan rate of 4 s. This performance can be greatly improved by running the algorithm on faster commercially available machines rather than on the SUN Sparc 2.

In the next future, we intend to extend the capability of the algorithm to handle additional data (range rate, elevation angle, target identity) and also introduce more sophisticated target models, e.g. replacing the target state model with an augmented sixth-order model (which estimates acceleration) only for the duration of the maneuver. Optimization of processing time is another topic of investigation. Additional areas of future work refer to the processing of recorded live data, the extension of the MHT algorithm to the multisensor tracking case and mapping of the algorithm, which is inherently parallel, on to a network of workstations.

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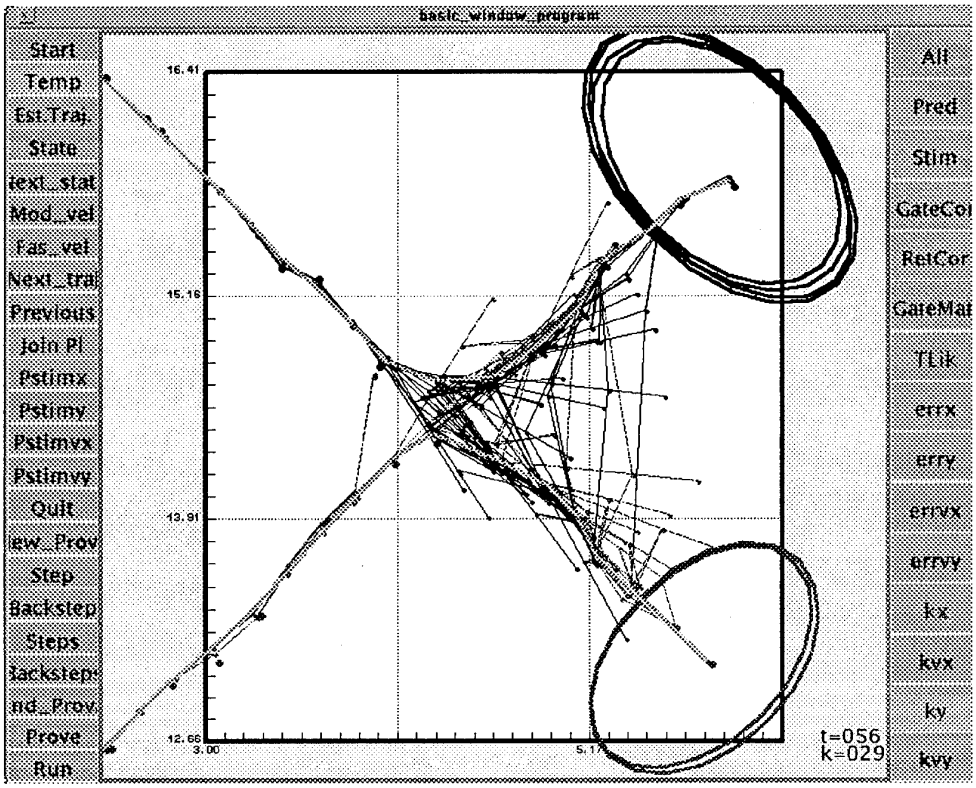


Figure 4. Typical display from MHT algorithm.

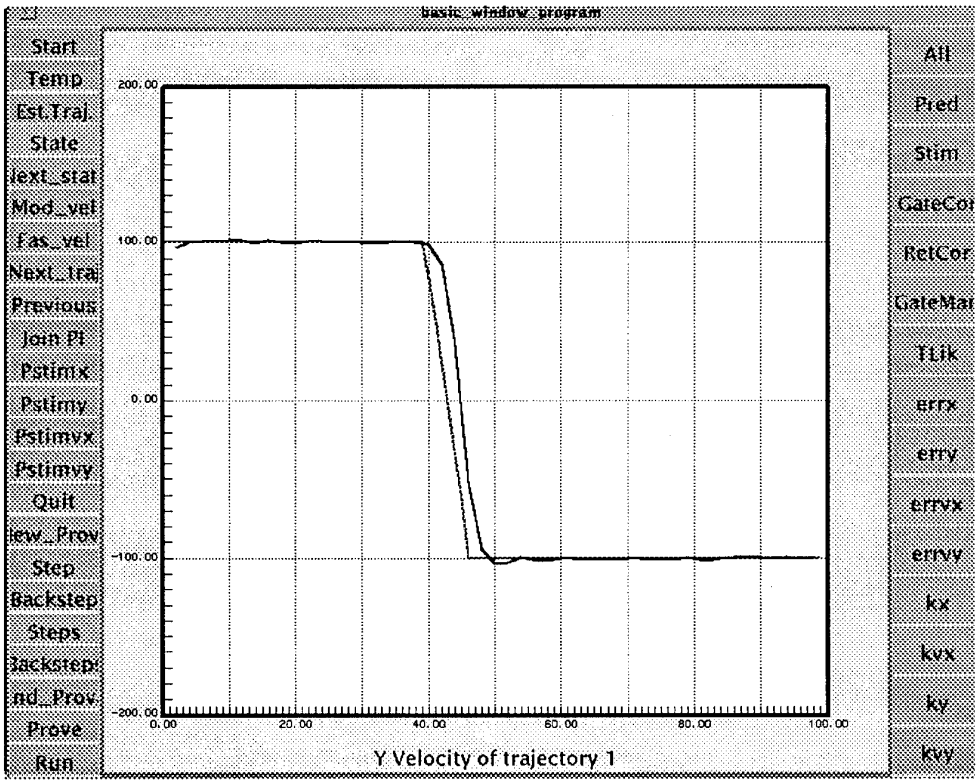


Figure 5. Typical display of tracking errors.

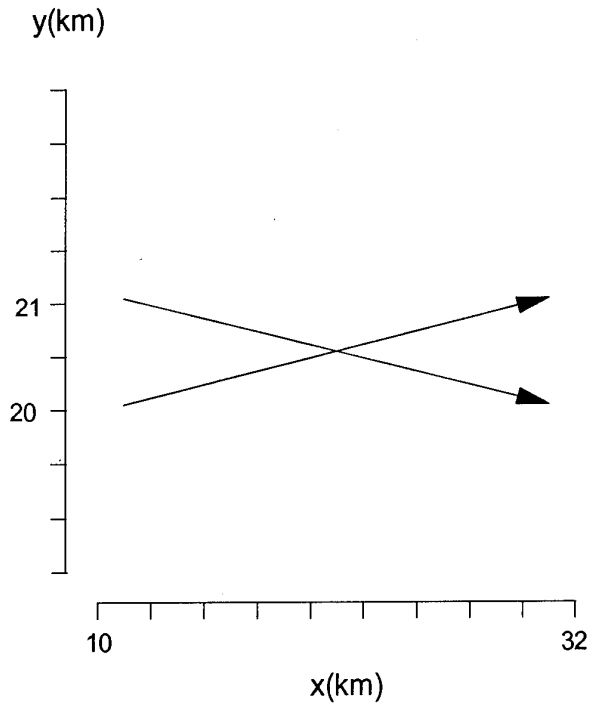


Figure 6a. Two straight-line crossing targets.

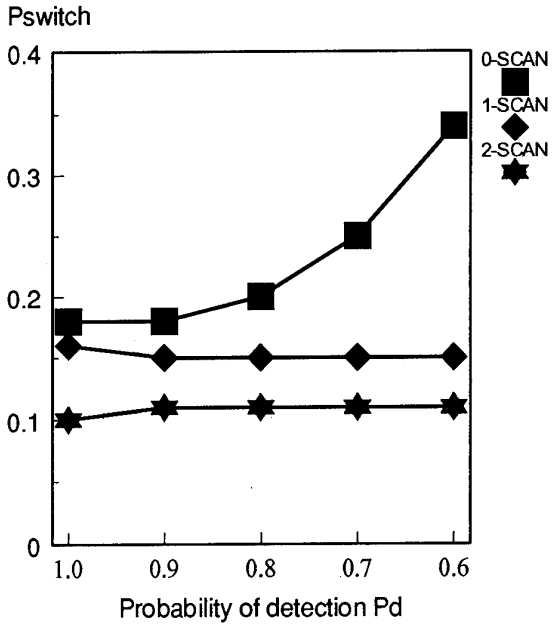


Figure 6b. Probability of switching the two targets.

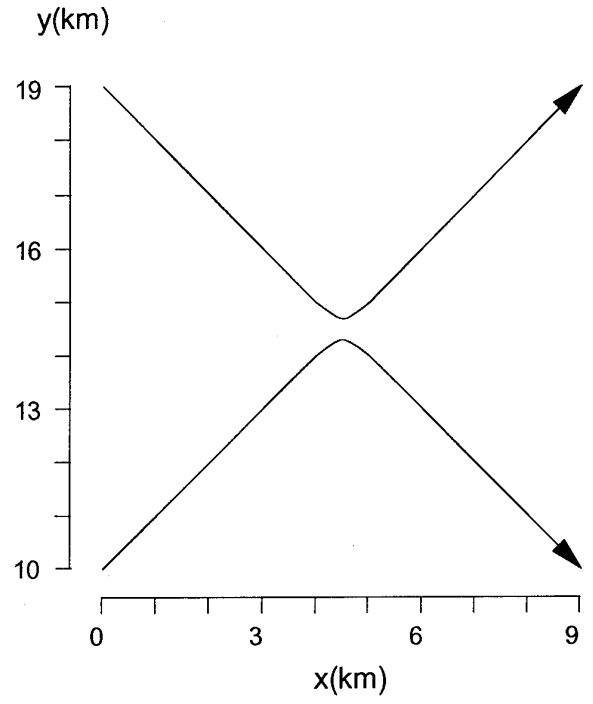


Figure 7a. Two non-crossing targets.

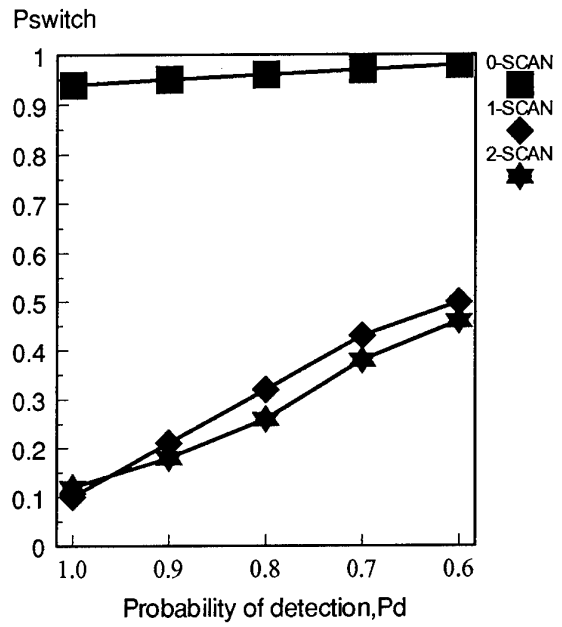


Figure 7b. Probability of switching the two targets.

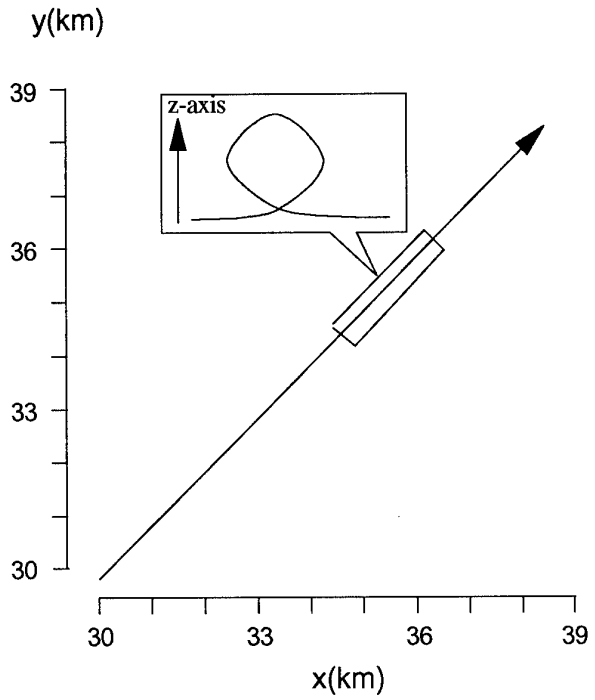


Figure 8a. Straight-line target with looping maneuver.

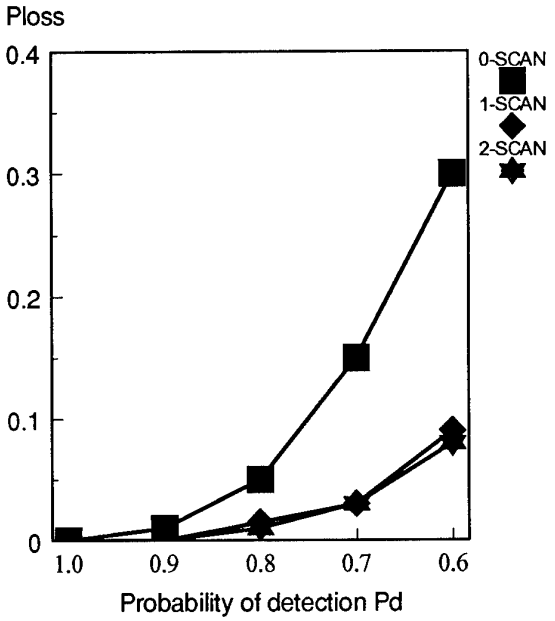


Figure 8b. Probability of loosing the target.

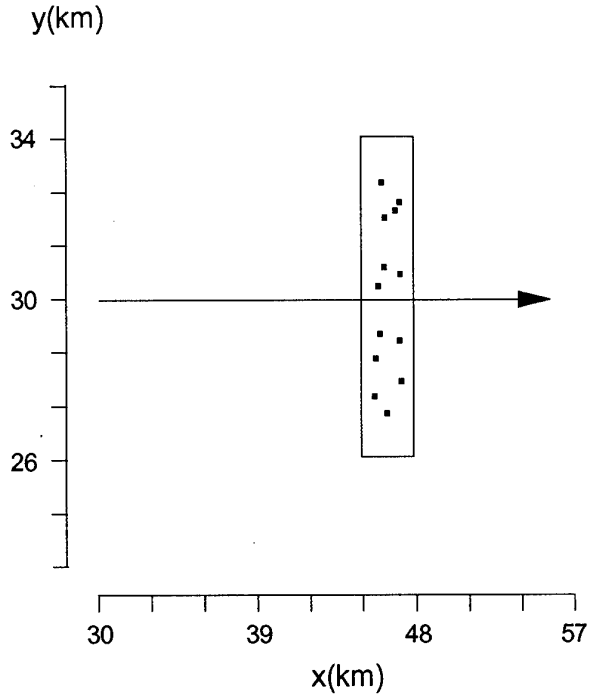


Figure 9a. Straight-line target in clutter.

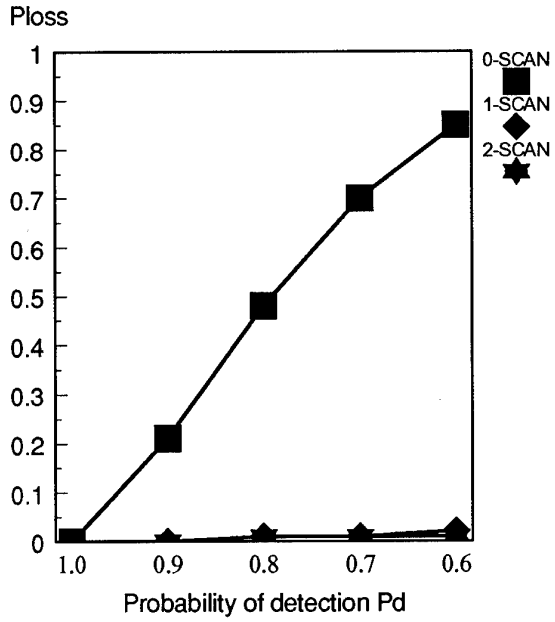


Figure 9b. Probability of loosing the target.

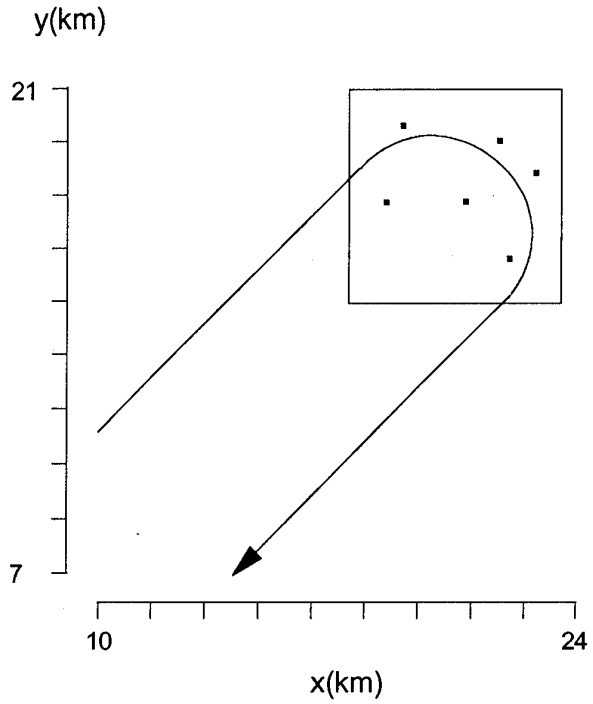


Figure 10a. Maneuvering target within clutter.

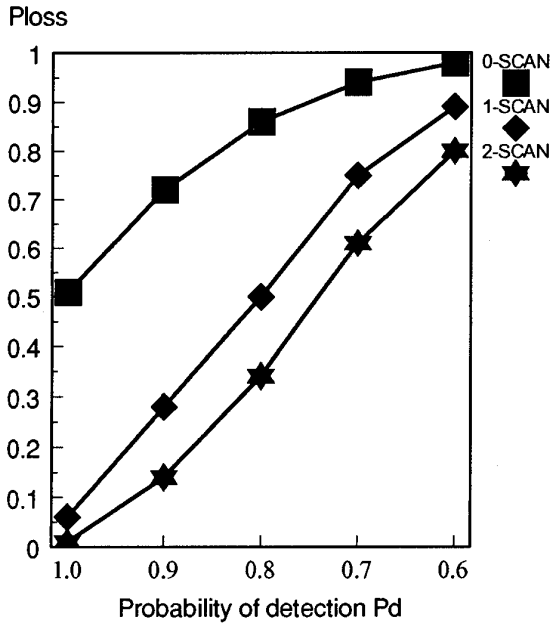


Figure 10b. Probability of loosing the target.

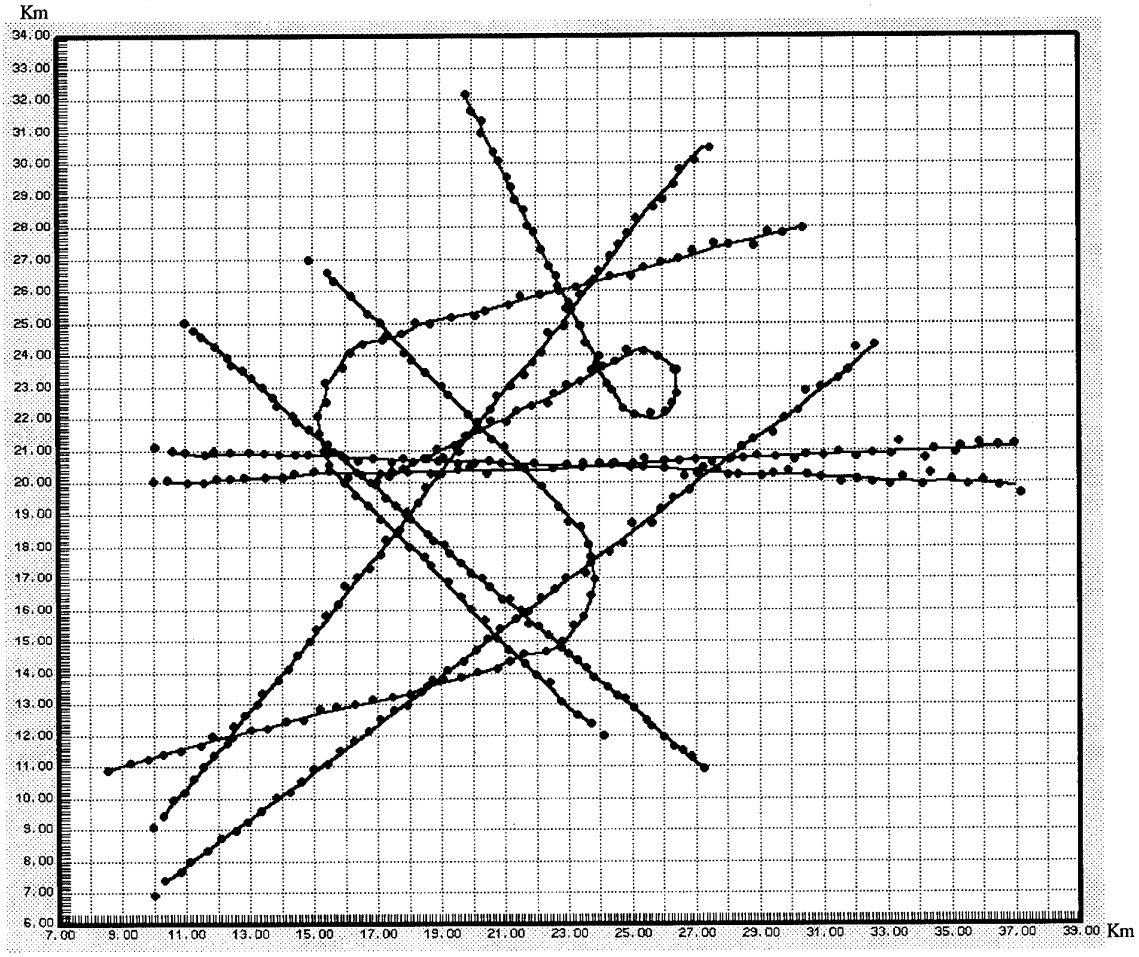


Figure 11a. Plots and MHT tracks for eight interacting targets.

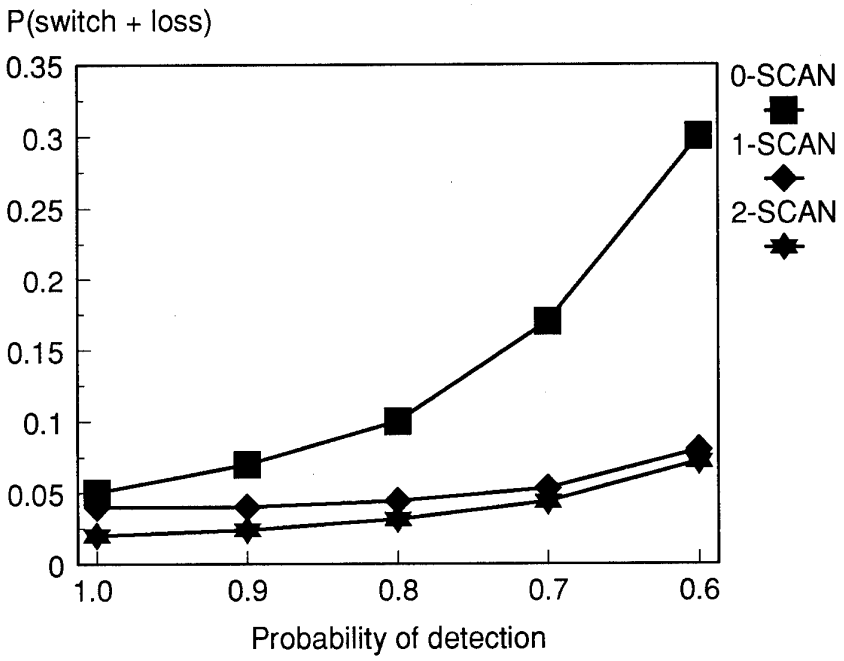


Figure 11b. Probability of incorrect tracking.

A fast parallel computing machine for real time decision making: Applications to real time processing, war games, forest fire and fluid dynamics models.

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Abstract

The hardware prototype of a MIMD (multiple instruction multiple data) computing machine dedicated to the processing of large amounts of data in real time is described. The Lattice Automata Machine (LAM) is based on a cellular automata architecture, but has extended features as for example "non-local" and "time dependent" programming. The front end of LAM is hosted in a personal computer, used as an input-output peripheral. This machine has been developed for dedicated programming of systems of partial differential equations and processes up to 1.15 Giga events per second. One of the hardware characteristics introduced in this machine is the possibility of memory replication in different data banks, enabling the simultaneous access to different RAM positions.

1 - Introduction

Large scale computing is a necessity in engineering, basic research and computer assisted decision making, [3], [7], [8] and [10].

Multicomponent real systems are extended in space and evolve in time according to the evolution laws of individual subsystems and to the interactions with local and nonlocal neighbours, fig. 1.

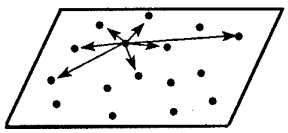


Figure 1: Spatial distribution of an extended system and interaction laws with local and nonlocal neighbours.

Data characterizing subsystems at time t depend of data of several neighbour subsystems at time $t-1$. The performance of computing machines to calculate time evolution of extended systems is low due to the sequential order in which data are collected for calculations. In real systems time evolution is intrinsically parallel, in the sense that the whole system is updated in one real time step, and each subsystem can use the information of other subsystems simultaneously.

Vectorial or multiprocessor machines achieve computing performance by grouping together independent computing steps and vectoring independent data sets, reducing the number of sequential clock cycles, and consequently the overall computing time. However, the simultaneous access to data sets is not possible, and this is a critical path in computation.

The objective of this paper is to show that computer performance is increased by a different organization of the data available for computing, transforming dynamically every distributed system into a local system. Every distributed system can be transformed into a local system trough the replication of data in memory (redundancy), enabling the simultaneous access to different memory positions. Under these conditions, the advantages of parallel and vectorial processing lead to much faster computations when compared with traditional machines.

The increase of data memory leading to redundancy, the independence of program memory from data, and the introduction of parallel computing enables real time computing, achieving 1.15 Giga events per second in a small machine. The enhancement of computing time obtained by replicating input data permits, virtually, the simultaneous access to different RAM positions.

The architecture we propose has been developed to solve problems such as war games, fluid flow, fire propagation, image processing and multiparticle dynamics. All these problems have in common the fact that the individual elements are distributed in a two-dimensional space (a plane), and evolve in time according to some dynamic law, described by the functional equation

$$F\Big(\frac{\partial^2\phi}{\partial x^2},\frac{\partial^2\phi}{\partial y^2},\frac{\partial^2\phi}{\partial t^2},\frac{\partial^2\phi}{\partial t\partial x},\frac{\partial^2\phi}{\partial t\partial y},\frac{\partial^2\phi}{\partial x\partial y},\frac{\partial\phi}{\partial x},\frac{\partial\phi}{\partial y},\frac{\partial\phi}{\partial t},\phi,x,y,t\Big)=0 \tag{1}$$

where x, y and t are space and time variables and $\phi(x,y,t)$ represents, for example, the velocity field in a fluid or the distribution of individuals in two opponent armies. The conversion from the functional form (1) to a discrete form is done by the usual finite differences approximations, as for example, $\frac{\partial^2\phi}{\partial x^2} \rightarrow (\phi_{i+1}+\phi_{i-1}-2\phi_i)/(\Delta x)^2$.

The most important characteristics of the hardware prototype described here are:

1) Parallel calculations in multidimensional spaces, accessing up to 18 local and non-local neighbours, with the same performance.

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2) Total independence of data and program memory buses.

3) Capability to perform dependent or independent tasks, partitioning base memory, program memory and program control units.

4) Dedicated display independent from the front end.

5) The programming language is C, adapted to the specific abstract machine model. The front end is hosted in a personal computer.

6) Direct implementation of systolic arrays.

To simplify this exposition, we now consider a class of systems having a simple implementation under the general computing scheme presented here. In the last section, the characteristics and the basic architecture of the hardware prototype is described.

2 - A cellular automata model

Since the work of von Newman on self-replicating machines [2], [9], cellular automata played an important role in theoretical computer science. Recently, cellular automata models have become popular with the work of S. Wolfram [11] on its potential applications in physical sciences. The possibility to explain the emergence of complex structures from very simple rules, simply based on the algebra of logics, seems to be a promising field of research.

As in Turing machines, cellular automata are arrays of memory positions that hold symbols from an alphabet. The symbols in each memory position evolve in time according to some local rule. These systems simulate an universal Turing machine, as the popular game of life [1].

The simplest example of a cellular automata is obtained with an infinite strip that holds zeros and ones. The state of the strip at time t is a bi-infinite sequence of symbols. At time $t+1$, the sequence evolves according to the local rule $x_i^{t+1} = f(x_{i-1}^t, x_i^t, x_{i+1}^t)$, where f is some boolean function and x_i is the value of the boolean variable at position i. For example, figure 2 represents an evolving configuration for an initial finite string with the rule $f(x_{i-1}^t, x_i^t, x_{i+1}^t) = x_{i-1}^t \oplus x_i^t \oplus x_{i+1}^t$.

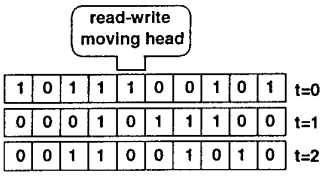


Figure 2: Time evolution of a cellular automata in a finite array with periodic boundary conditions. Time evolution is calculated with the boolean function $f(x_{i-1}^t, x_i^t, x_{i+1}^t) = x_{i-1}^t \oplus x_i^t \oplus x_{i+1}^t$. We represent the read-write moving head that holds the information on the state of the processor.

To calculate the time evolution of the string of bits from the string state at time t to $t+1$, the machine head performs five moves to update each site. If n is the length of the strip holding the information, and m is the breadth of the boolean function f, the number of elementary steps to actualize the strip from time $t = 0$ to time $t = k$ is

$$\text{Elementary steps} = k(2m-1)n \qquad (2)$$

Suppose now that we replicate twice all the information in the initial strip according to the rule of figure 3.

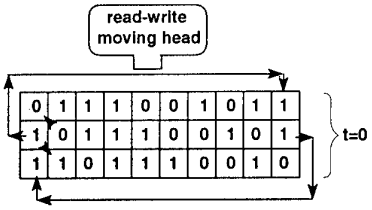


Figure 3: Replication of initial data of the cellular automata of figure 2, with periodic boundary conditions.

From the data set of figure 3, the cellular automata does not depend on the immediate neighbours, and the local time evolution is calculated from the data in the actual position of the read-write head, leading to a much faster actualization of the string. For a strip with n positions and memory replication $m-1$, the number of computing steps after evolution at time $t = k$ is

$$\text{Elementary steps} = kn \qquad (3)$$

Comparing (2) with (3), linear replication of memory storage enabled an linear decrease in computing time.

In this simple example we have shown that it is possible to obtain an increase in computer performance by the replication of data in memory.

3 - War games

The Lencaster's combat models for two armies describe the temporal evolution of the number of combatants of opposite armies as a function of operational and combat losses by unit of time, and of the reinforcement rates. These models do not incorporate information about tactical disposition on the battle field. However, spatial effects can be taken into account easily.

To restrict our discussion we take the situation of two guerrilla troops. Let A and B be the number of combatants of the two guerrilla troops without reinforcement. The Lencaster equations [4] for the time evolution of the number of effectives is

$$\frac{dA}{dt} = -aA - bAB$$
$$\frac{dB}{dt} = -cB - dAB \tag{4}$$

where the parameters a and c are operational losses (in general a and c are close to zero) and b and d describe the interaction between the two forces. For $a = c = 0$, the phase space analysis of the above system of equation shows that, for initial troops $A_0 > 0$ and $B_0 > 0$, A wins if $B_0 + dA_0/b < 0$, and B wins if $B_0 + dA_0/b > 0$. Incorporating tactic disposition, random motions in the battle field and obstacles into these equations, we obtain

$$\frac{dA}{dt} = -aA - bAB + D_A D(x,y)\left(\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2}\right)$$
$$\frac{dB}{dt} = -cB - dAB + D_B D(x,y)\left(\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2}\right) \tag{5}$$

where D_A and D_B are the mobility coefficients of both troops, and $D(x,y)$ carries the information concerning landscape and geometry. Eq. (5) can be easily extended to describe the evolution of any combat arrangement, including conventional-conventional or guerrilla-conventional interactions and progression in the battle field.

For $D(x,y) = 1$ (no obstacles), it can be shown [5] that the time evolution of the number of effectives is given by

$$A_{i,j}^{t+\Delta t} = A_{i,j}^t - b\Delta t A_{i,j}^t B_{i,j}^t + D_{AB}\left(G_1(A_{i,j}^t) + G_2(A_{i,j}^t) + G_3(A_{i,j}^t)\right)$$
$$B_{i,j}^{t+\Delta t} = B_{i,j}^t - d\Delta t A_{i,j}^t B_{i,j}^t + D_{AB}\left(G_1(B_{i,j}^t) + G_2(B_{i,j}^t) + G_3(B_{i,j}^t)\right) \tag{6}$$

where $D_{AB} = D_A/\max\{D_A, D_B\}$, $D_{BA} = D_B/\max\{D_A, D_B\}$, and

$$G_1(A_{i,j}^t) = (A_{i-1,j}^t + A_{i+1,j}^t + A_{i,j-1}^t + A_{i,j+1}^t - 4A_{i,j}^t)/12$$
$$G_2(A_{i,j}^t) = (A_{i-1,j-1}^t + A_{i+1,j-1}^t + A_{i-1,j+1}^t + A_{i+1,j+1}^t - 4A_{i,j}^t)/16$$
$$G_3(A_{i,j}^t) = (A_{i-2,j}^t + A_{i+2,j}^t + A_{i,j-2}^t + A_{i,j+2}^t - 4A_{i,j}^t)/96 \tag{7}$$

The indices (i,j) refer to space location $(x,y) = (i\Delta x, j\Delta x)$. The space scale of the system is $\Delta x = \sqrt{4\max\{D_A, D_B\}\Delta t}$, and Δt is chosen according to some realistic system of units, determined by the mobility constants D_A and D_B.

To compute the time evolution of system (6), we choose two independent lattice planes associated to each force. Each lattice point carries, for example 16 bit, representing the number of effectives at that position. Given an initial distribution of troops, we need to analyse twelve neighbours at each site, then calculate the interaction with the elements of the other group, and repeat the calculation for all the lattice points. An arrangement for the fast computation of this system is presented in fig. 4.

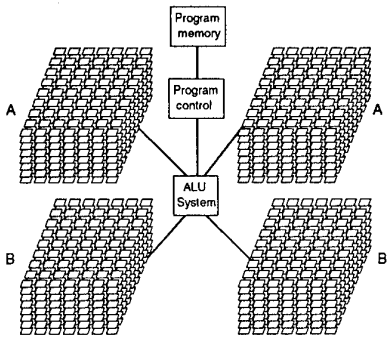


Figure 4: Geometric arrangement for fast computing of the system (6). Each square holds a bit and the vertical string in the (x,y) plane represents the number of effectives in this region.

The two lattices associated to each troop carry the same information. So, the arithmetic and logic unit (ALU system) picks simultaneously two neighbouring points in A and two neighbouring points in B and makes the calculations according to (6). The choice of neighbouring points is selected by a Program Control Unit according to the instructions in the Program Memory. As all these operations are done in parallel, we obtain a very performing computing system.

According to the hardware implementation of the LAM, we calculate the number of effectives of the two armies in a grid of 512×256 in 65.76 ms, with a color display proportional to the number of effectives.

4 - Fluid dynamics models

Following the basic principles developed so far, we can interact with the LAM and calculate fluid flow and fire propagation in real time.

Figure 5 shows the time evolution of a pollution front in the Tagus Estuary. The geometry of the estuary was taken from a satellite image and the boundary has been drawn over the scenery. In this application we have introduced, the effect of tides, constant flux boundary conditions and variation of the magnitude of the velocity field.

The fluid flow is calculated in the LAM. From the front end hosted in a personal computer (PC), we can control the display velocity, pick up frames for further processing in the PC, and introduce and change data

conditions. Figure 5 is the front end display with the fluid flow calculated by the LAM and already processed in the PC.

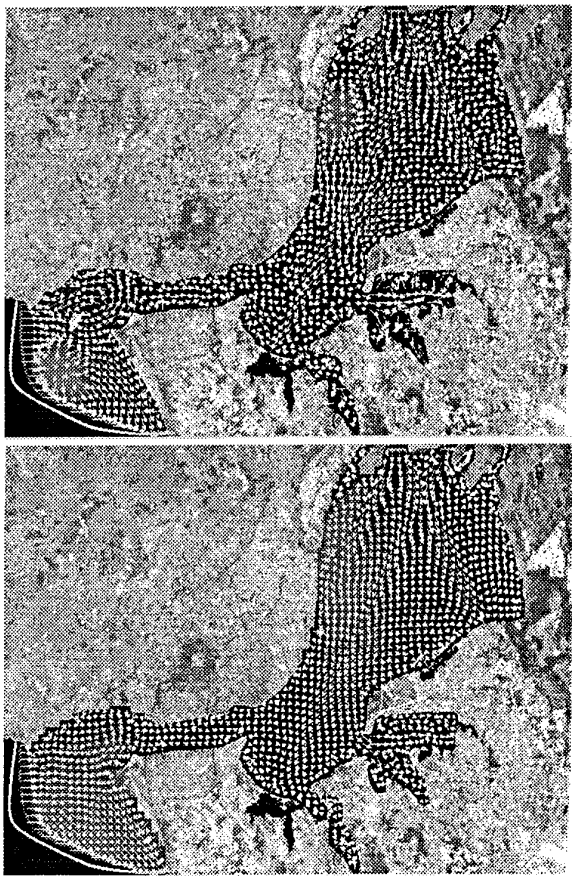


Figure 5: Evolution of a pollution front in the Tagus Estuary.

5 - The hardware prototype

The Lattice Automata Machine has been constructed with a total base memory of 1024 × 1024 cells. Each cell has 18 layers with one bit of information, fig. 6. A Base Memory block (BM) has 256×512 bit of storage memory. Connecting together all the BM blocks through a programmable switch (PSW), we achieve up to 1024 × 1024 bit per layer.

The first sixteen basic layers have two Program Memories per layer (PM) and eight Program Control Units (PCU). These units interpret the program instructions in the PM to perform the access to the Base Memory (BM) through the PSW and a particular relative displacement on the coordinates of the BM (defined in the PM). Two more layers with independent PM are defined for control purposes. Each PM can store up to 64K time dependent programming instructions.

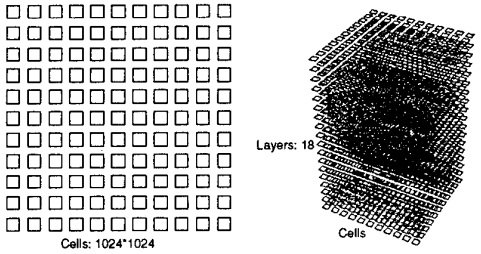


Figure 6: Total base memory of the Lattice Automata Machine.

There are eight Lookup Tables (TAB) and four Programmable Arithmetic and Logic Unit (PALU). In each clock cycle we can access the TAB or the PALU, but not both. Each TAB sees the output of the corresponding BM (or I/O from other source controlled by the PCU) for all the 18 layers, giving the required 18 bit answer and 4 or 8 bit color display. The display information is stored on FIFO (first in first out) memory and processed independently of the data in the BM.

The PALUs split the lattice memory into two groups. They compute efficiently products, cumulative additions with 16 bit, data copies and logic operations between the two groups. If a memory group is a copy of another memory group, we can at least double the speed of operation and simultaneously preserve the lookup tables for other kind of local rules.

The PM, BM, PSW, TAB and PALU work in parallel. The main computer cycle is 16.44ms (60.8 Hz) where all the cells are updated (full configuration) and displayed. Moreover, this basic architecture is expansible in the sense that it is possible to connect directly two machines, obtaining twice the performance. The basic architecture of the LAM is presented in fig. 7.

We now classify the computer architecture of LAM, according to Flynn, Feng and Erlangen parallel architecture classification [6].

The Flynn classification is based on instruction and data streams. The multiple processors of LAM are working on multiple data streams. Such kind of computers are known as MIMD (multiple instruction multiple data). This classification does not contain any information about the type of connections used.

The Feng classification is based on the number of bits that are processed in parallel in a word, and the number of words that are processed in parallel. This classification does not allow to distinguish between multiprocessors and array processors nor does it distinguish processing levels from pipeline structures. In this case, LAM has 144, 1 bit, parallel processors: Feng(1,144).

The Erlangen classification was developed mainly in order to avoid the drawbacks of existing classification schemes. It is assumed that the performance

of the system is mainly determined by the processors and their capability to transfer information. The classification is based on the distinction between three processing levels, each one characterized by a number:

1) k: Number of Program Control Units (PCU) - Using counters, registers and microprogram devices, the PCU interprets a program instruction.

2) d: Number of Arithmetic and Logical Units (ALU) - The ALU execute sequences of microinstructions according to the interpretation process performed by the PCU.

3) w: Number of Elementary Logic Units (ELU) - Each ALU contains several ELUs, each dedicated to process one bit. The number of ELUs is commonly called the word-length w.

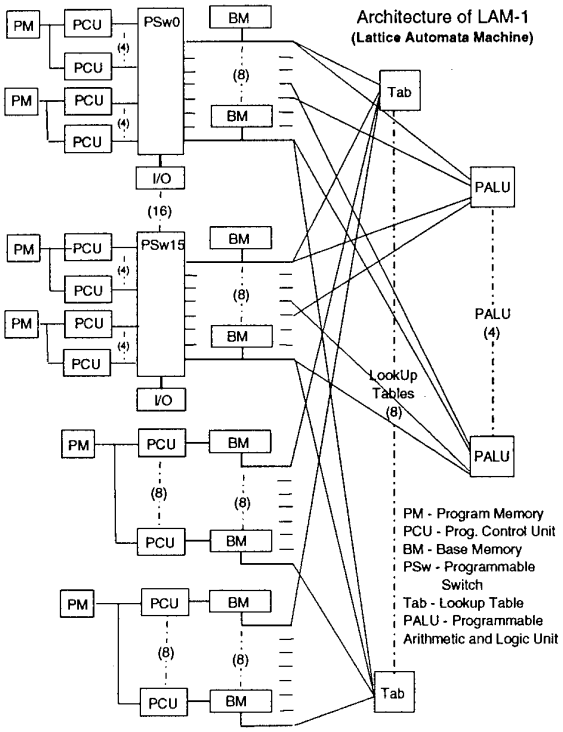


Figure 7: Basic architecture of the Lattice Automata Machine.

A computer configuration includes a number of PCUs (k), each PCU controlling a certain number of ALUs (d). All ALUs perform the same operation at any given time. Different systems exhibit different kinds of parallelism, which are uniquely attached to one of the three levels k, d and w.

If we disregard pipelining, the Erlangen classification will be Erlangen(computer type)= (k, d, w).

Comparing computer performance of LAM with other machines we have

Erlangen(LAM)= $(144, 8, 18)$.
Erlangen(IBM 701)= $(1, 1, 36)$.
Erlangen(SOLOMON)= $(1, 1024, 1)$.
Erlangen(ILLIAC IV)= $(1, 64, 64)$.
Erlangen(STARAN)= $(1, 8192, 1)$.
Erlangen(C.mmp)= $(16, 1, 16)$.
Erlangen(PRIME)= $(5, 1, 16)$.

The hardware prototype of LAM, presently under final assembly and test, is shown in fig. 8.

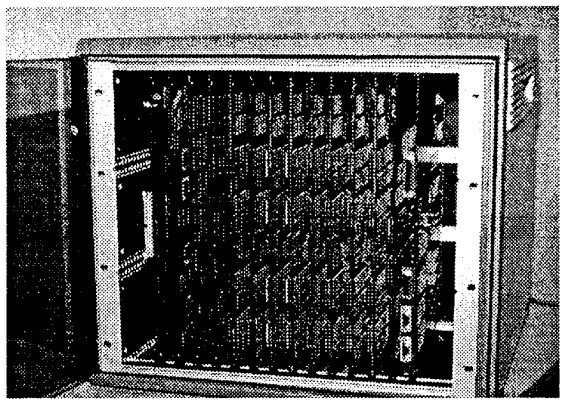


Figure 8: Lattice Automata Machine prototype.

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Large Scale Link 16/JTIDS Networks

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1. SUMMARY

The JTIDS Joint Program Office (JPO) has been on the leading edge of large scale multi-service, multi-platform, multi-mission JTIDS network design for several years.

Large scale network design studies conducted by the JPO have shown that if JTIDS is used efficiently and appropriately, it can meet expanding user and functional requirements, including multi-national operations. However, increasing reliance on JTIDS for theater communications will require a continued effort to develop more efficient ways to use it.

2. INTRODUCTION

The Tactical Digital Information Link (TADIL)-Joint Tactical Information Distribution System (JTIDS), known as TADIL J and also as NATO Link 16, represents the latest development in the field of TADILs. The first generation of JTIDS hardware which was fielded in the mid-1980s consisted of what is known as the Class 1 terminal. This terminal is large and bulky and, therefore, was integrated into only a few large command and control (C^2) platforms such as US and NATO E3s and some key ground command and control facilities. Since a jointly agreed upon digital message standard had not been developed by the time the Class 1 terminals were introduced to the user community, an Interim JTIDS Message Specification (IJMS) was developed and is still in use today. This initial Class 1/IJMS equipment very effectively supported coalition forces during Operation Desert Storm.

While the Class 1/IJMS equipment has been in use, the second generation of JTIDS hardware has been developed, was approved for full rate production in March of this year, and has already been installed in several operational systems, including the USS Carl Vinson carrier battle group. The initial second generation hardware is represented by the Class 2 family of JTIDS terminals. The Class 2 terminals are smaller, lighter, and more capable than their predecessors. In addition, the JTIDS user community (both US and international) have developed and continue to refine the more efficient and capable TADIL J (Link 16) message standard for use with the new generation of hardware.

This combination of hardware and message standard improvements has facilitated expansion of the planned JTIDS user base to include most major US C^2 platforms and a number of smaller non-C^2 platforms (e.g., fighters). The international cooperative development of the Multifunctional Information Distribution System (MIDS) Low Volume Terminal (LVT), which is even smaller than the Class 2, will further support proliferation to the non-C^2 platforms.

Recent Department of Defense pronouncement of Link 16 as the primary US tactical data link should lead to further expansion of the Link 16 user base. By the year 2000, many US tactical C^2 and non-C^2 platforms will be Link 16 capable.

3. PROGRAM STATUS

Over 200 Class 2 terminals have already been bought under low rate initial production contracts, of which nearly 75% have already been delivered. Current total projected buys of the Class 2 terminal are around 850. The total planned MIDS buys for US platforms number around 600 units, with the allies planning to buy additional units.

4. JTIDS NETWORK DESIGN EVOLUTION

The Link 16 digital message standard supports several different functional categories of information exchange (e.g., surveillance, engagement status). These categories are known as Network Participation Groups (NPGs). Network design is the process of allocating the finite capacity of the JTIDS/Link 16 system to a group of JTIDS equipped units (JUs) wishing to exchange information from the various NPGs with one another.

JTIDS uses a time division multiple access (TDMA) architecture with blocks of time slots allocated to various JUs for transmission of data on the different NPGs in which they wish to participate. The blocks of slots are sized in proportion to the expected capacity needs and are currently statically assigned. However, JTIDS operates in a line-of-sight (LOS) frequency band, so relays are required in order for JUs beyond LOS of one another to exchange information. Therefore, network design is not only concerned with allocation of JTIDS capacity for transmission of data, but it must also account for capacity required for receipt and relay transmission of data to provide desired platform connectivity.

4.1 Classical View of a JTIDS Network

The classical view of a JTIDS network is one in which many ground based JUs exchange data with one another via an airborne relay such as an E3. Such an airborne relay can provide connectivity among surface platforms up to 500-700 kilometers (km) apart, and between high flying airborne JUs up to 1800 km apart. We refer to such a network as a single (relay) hop network. The classical JTIDS network structure was envisioned to be of the single hop variety. In this classic network structure, it was envisioned that all JUs would share all of their surveillance data with each other, providing a common picture of the tactical situation for all to see.

4.2 First Wartime Use, Large Scale Air Defense Network

Though the classic JTIDS network was single hop, the JTIDS system is designed to support multiple relay hops, allowing the design of networks with much wider information

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distribution potential. In fact, the first wartime use of JTIDS in support of Operation Desert Storm required multiple relay hops to collect and distribute information over the large Saudi-Iraq-Kuwait border region. It turned out that not much thought had been given to the design of such large scale multi-hop network structures. Consequently, there were no existing network designs which could be used, and a special multi-hop network design was created to support the operation.

Though coalition forces ultimately involved in the Gulf war ranged from the Red Sea to the Persian Gulf, there were few JTIDS equipped platforms in theater. In fact, the Naval forces operating in the Red Sea and the Persian Gulf were not JTIDS equipped, so the network, though large by previous standards, only covered a relatively small portion of the overall theater geography and included few direct JTIDS participants.

Despite using the older Class 1 JTIDS equipment with its limitations, sufficient capacity was available for the network design to provide a fully shared surveillance picture among all of the front line air surveillance sensors. This picture was extended to include a ground site which had the capability to participate in the JTIDS network exchanges, and to translate the JTIDS/IJMS picture to TADIL B for distribution through the theater TADIL B network to other non-JTIDS participants like the Joint Forces Commander (JFC) and his Air Component Commander (JFACC) in the rear. Unfortunately, the capacity of the existing TADIL B systems is much lower than JTIDS, so the flow through the TADIL B structure was much slower than that experienced among the JTIDS equipped players.

Despite the limitations in JTIDS equipped platform availability, and in the Class 1's capabilities, the JTIDS network performed exceedingly well, and formed an effective backbone for the JFC's Theater Air Defense (TAD) network architecture.

4.3 Large Scale Air Defense Network Studies

Following the Gulf War, the JPO was requested to answer several questions relative to the new JTIDS Class 2 systems' capabilities. The first was to investigate what added benefits the Class 2 equipment would have brought to Operation Desert Storm, assuming only that the Class 1 terminals used were replaced with the new Class 2 terminals. The second question was to address what kind of JTIDS network might have been fielded if all of the US forces involved in the war which were scheduled to receive the new Class 2 terminal had had it.

A network design analysis showed that the answer to the first question was that the new JTIDS (i.e., Class 2 terminal and TADIL J) could have supported the reporting of three to four times as many tracks per track update cycle as the Desert Storm network had (this figure is six to eight times the Desert Storm network capacity using one of the Class 2 terminal options which allows trading a slight amount of jam resistance for additional throughput).

The answer to the second question was much more complex, because it increased the number of JUs, covered a much larger geographic region, and required additional information categories. To answer the question, the JTIDS JPO created an expanded network covering the entire Southwest Asia theater from the Red Sea to the Persian Gulf. The network included Navy assets in both bodies of water, and JTIDS equipped air defense assets from all of the other US services across and above the land mass separating them.

4.3.1 *The Common Picture Concept*

While the actual Desert Storm network coverage was still small enough to justify the concept of a fully shared surveillance picture, the expanded Persian Gulf to Red Sea network was large enough to bring this concept into question. For example, in designing such a large network, one must ask whether it is necessary (or even useful) for Navy units in the Persian Gulf to have a near-real-time picture of the tactical situation in the Red Sea. Many such questions must be answered in the very large scale represented by the Persian Gulf to Red Sea network. Certainly for some players in such a large theater (e.g., the JFC or JFACC), a view of the tactical picture across the whole theater would be very desirable, but the players with such broad information needs are exceptions rather than the rule.

4.3.2 *Finite Resources*

If communications, information processing, and information display capacities were unlimited, one might take the view that all available tactical information in theater should be distributed to everyone, permitting each participant to display any data at any time. However, even though the new JTIDS offers network communications capacities many times that of existing TADILs, processing power is orders of magnitude higher than it was only a few years ago, and display technology has vastly improved, all of these resources are finite. Consequently, as network size and numbers of participants grow, there is a point at which the limits of these resources begin to come into play.

4.3.3 *Capacity and Connectivity Tradeoffs*

The result is that, as network size and participation grow, there is a point at which tradeoffs of these finite resources must begin to be made. For example, the new JTIDS provides ample capacity for the battle group in the Persian Gulf to implement all of the local internal battle group information exchanges they deem necessary, but if there are additional JTIDS equipped sensors set up ashore that could provide them with some advanced warning of approaching threats from the west, it may be useful to monitor that data via JTIDS as well. If this could be implemented without sacrificing any local battle group information exchange capabilities, all is well and good. But then if additional sensors are set up further to the west, maybe it would be desirable to monitor them as well. Eventually, it may be that monitoring more and more distant data uses up so much capacity that it causes the battle group to have to give up some of its desired local information transactions (e.g., a local JTIDS voice channel).

4.3.4 *The Cost of JTIDS Relay*

In addition, getting data routed to distant parts of a large network usually involves the use of many relays, and the relays have to use double the capacity for information they are required to relay. This is because the ultimate recipients of the data only need to commit enough capacity to receive the data, while the intervening relays must not only use capacity to receive the data, they must also allocate the same amount of capacity to relay it.

Fortunately, the new JTIDS was designed with many capacity enhancing features that allow it to accommodate network structures many times larger (geographically and in numbers

of participants) than Class 1 terminal and IJMS networks before such tradeoffs are required. However, the expanded Persian Gulf to Red Sea network is large enough to require consideration of connectivity and capacity tradeoffs. Operationally it becomes a matter of trading off local capabilities to support wider distribution of data. This then translates into having to make judgments as to whether greater benefit is derived from the wider distribution of data versus the potential loss of local capabilities.

Connectivity versus capacity tradeoffs are required in large scale networks. Trades were made in the expanded Persian Gulf to Red Sea air defense network by making selected connectivity reductions to improve local tactical capabilities (e.g., fighters don't have to use some of their capacity to listen to distant air tracks (e.g., over 500 miles away), so they are able to support a higher local fighter-to-fighter target exchange rate). The reductions attempted to recognize special roles and missions of certain key players in the network like the JFC and JFACC and to continue to provide them the entire 'big picture.' To maximize other (e.g., fighter) tactical platform local data exchange capabilities (and, therefore, hopefully mission effectiveness), they were scheduled to monitor their local area surveillance picture, and only those other sensors within several hundred miles around, but not all theater sensors.

4.4 Addition of Theater Missile Defense

While contemplating the requirements of a communications system to support Theater Missile Defense (TMD), the Ballistic Missile Defense Organization (BMDO) took note of the large scale network design work being done in the JTIDS and air defense communities. TMD has a theater-wide communication requirement, and JTIDS was showing its potential for providing theater-wide communications capabilities. One particularly attractive feature of JTIDS was that it was already planned to be installed in many of the platforms that would be involved in TMD.

To evaluate the feasibility of using JTIDS to concurrently support both TAD and TMD, the BMDO requested that the JPO perform a JTIDS TMD Utility Analysis, using the network design approach which had been used in the evolving air defense network expansion studies. The plan was to use the expanded Persian Gulf network, and another large scale air defense network design based on a Northeast Asia (NEA) scenario as baseline air defense networks. The services would then define additional platforms and communications required to be added to those networks to support TMD. The BMDO was particularly concerned with the potential impact of the added TMD communications on the air defense capabilities of the baseline networks.

The resulting TAD/TMD network designs and loading analysis results convinced the services and the BMDO that if TMD communications requirements were integrated efficiently, then JTIDS could absorb the added TMD message traffic with minimal impact on air defense. Based on these results the BMDO endorsed JTIDS as the primary terrestrial data link in support of TMD. Since that time, the TMD community has been busy developing new Link 16/TADIL J messages to actually implement the BMDO decision.

4.5 Emerging Large Scale Network Design Issues

As geographic coverage expands, the network capacity available for sharing of sensor tracks among widely dispersed groups of sensors and weapons systems (which we call the joint Wide Area Surveillance (WAS) net structure) has to be subdivided among the different geographic areas (which we call 'zones'). For networks with several zones (e.g., the two air defense baseline networks), the WAS capacity allocations to the zones appear to be adequate to handle a concurrent air and missile threat at the levels specified in the scenarios studied. However, if the WAS participants within a zone cannot dynamically share the zone capacity, the zone allocation has to be further subdivided among the zone members. If there are large numbers of members in a zone all desiring access to the zone's WAS capacity, without dynamic capacity sharing capabilities, the result could be marginal or inadequate individual allocations.

4.5.1 *Dynamic Capacity Sharing Needed*

As concurrent TAD/TMD networks grow in size and membership, the need for dynamic capacity allocation grows. Fortunately, the US and the UK recognized the approaching need for dynamic capacity sharing some years ago, and developed a dynamic capacity sharing scheme called Time Slot Reallocation (TSR). Unfortunately, few planned JTIDS platforms have yet committed to the use of TSR, so large scale network designs must still statically subdivide available capacity so many ways that optimum theater wide mission effectiveness cannot be achieved. Continuing network design studies and analyses are heightening awareness of the need for dynamic capacity sharing, and all of the US services as well as the BMDO now officially recognize the benefits of TSR and are pursuing investigation into its more widespread implementation.

4.5.2 *Non-JTIDS Range Extension Needed*

The large scale concurrent TAD/TMD communications studies that have been done to date assume that JTIDS will be used to support long haul communications within the theater. However, as network size and participant numbers increase, the increasing long haul relay burden can take away capacity a platform could have used to enhance its own local tactical capabilities and mission effectiveness. Though it possesses capabilities which allow it to handle many theater long haul communications requirements, JTIDS was never intended to support such long haul communications on a large scale.

Long haul non-JTIDS communications alternatives which can mesh well with JTIDS are needed (the Desert Storm network architecture used mismatched TADIL B).

5. CONCLUSIONS

JTIDS networks have been designed which demonstrate coverage in both area and mission, well beyond that originally conceived of for the data link. However, JTIDS capacity for such large scale concurrent TAD/TMD networks is being strained. Stress on JTIDS networks due to continued expansion of JTIDS users and functions can be mitigated with improvements in efficiency of use. Two methods for improving efficiency were discussed: 1) reduction of the long haul relay burden from JTIDS units through development and use of non-JTIDS TADIL J communication, and 2) the implementation of dynamic capacity sharing capabilities such as TSR in key JTIDS platforms.

These conclusions are based on large scale networks for which we have assumed unrestricted JTIDS operation. Small scale concurrent TAD/TMD contingency operations with peacetime JTIDS frequency allocation restrictions may be required. The viability of such networks also needs to be investigated.

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THE IMPACT OF ASYNCHRONOUS TRANSFER MODE COMMUNICATIONS ON TACTICAL MILITARY COMMAND AND CONTROL

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1. Summary

Improved communications technology often leads to improved command and control capabilities and, in some cases, to new modes of operation. Asynchronous transfer mode (ATM) communications has the potential to be the kind of technology that will permit significant changes in both the command and control architecture and physical relationships of component and support elements. This paper will describe ATM technology and its application, possible impact, and current status with respect to military situations.

2. Introduction

Effectively fighting a modern tactical war, and efficiently using resources, increasingly depends on the skilled processing and dissemination of data, including imagery. Moreover, making the right tactical decisions requires the collaborative efforts of commanders and their staffs across components and echelons. This mutual collaboration requires sharing data and using video teleconferences to facilitate discussions, and the communications infrastructure must support these activities.

The existing tactical communications resources are often among the most difficult to use efficiently because of the architectural constraints imposed by switched circuits and the hardware and software which control them. The recent introduction of a limited number of packet data networks has provided increased flexibility in the use of bandwidth insofar as any user is allowed to use as much bandwidth as he needs as long as it is available. However, even the performance of these packet systems, which are most efficient for asynchronous message traffic and datafile transfers, begins to degrade as the aggregate bandwidth demand exceeds some nominal threshold; and switched circuits remain necessary for those purposes, such as voice and video, that require isochronous operation with low latency and stable time references.

ATM technology holds the promise of combining the benefits of both packet and switched circuit systems, thereby yielding a more integrated, efficient, and effective way to both transfer data and to provide voice and video service. It will permit a different, more flexible architecture, and it should also allow more coordination between geographically dispersed elements.

3. ATM Overview and Capabilities

ATM is an emerging communications technology that is designed to internetwork voice, video, and data applications over a common physical link. It is a connection oriented technology based on the concept of segmenting all digital data flowing through the network into short, fixed length cells that can be processed rapidly within ATM switches and network interfaces. This technology also permits the interleaving of cells from multiple users and multiple application types on the same physical media to allow both for efficient use of the network bandwidth and for time-varying bandwidth allocations, commonly referred to as *bandwidth-on-demand.*

ATM Cell Structure. All digital telephony (voice), video, and data sent over ATM-based networks is segmented into 53 byte fixed length cells which have 48 byte payloads. The same basic 53 byte cell structure is used regardless of whether the network is a local area network (LAN), metropolitan area network (MAN), or a wide-area-network (WAN). Consequently, gateways are never required to translate protocols with ATM technology.

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Figure 1 shows the ATM cell structure for cells at the user network interface (UNI). The fields in the diagram are:

1. GFC (generic flow control) regulates the flow of cells during periods of congestion.

2. VPI (virtual path indicator) provides a logical grouping of virtual circuits and identifies a node-to-node path between the source and destination ports.

3. VCI (virtual channel indicator) identifies cells within a data stream.

4. PTI (payload type indicator) distinguishes payload data as either user information or network configuration information.

5. CLP (cell loss priority) determines which cells may be dropped when a switch encounters congestion.

6. HEC (header error correction) detects errors in the header (only) and corrects single bit errors. Cells are dropped if header errors cannot be corrected.

For ATM cells being transmitted between switches, at the network-network interface (NNI), the GFC field is subsumed into the VPI to allow sixteen times more VPIs.

The ATM Protocol Architecture. The ATM protocol architecture has two separate protocol layers, the ATM layer and the ATM adaptation layer (AAL), that closely approximate the functionality of the link and the network layers, respectively, of the seven layer OSI Reference Model. The ATM protocol layers include some of the characteristics of other OSI Reference Model layers, functioning as the data link, network, and transport layer protocols because they provide error detection, routing, and (end-to-end) permanent and switched virtual circuits. Figure 2 illustrates a mapping of the ATM protocols to the OSI Reference Model. The ATM Protocol Architecture shows the ATM layer and the AAL replacing the data link and network layers.

An application can access the AAL directly, consequently, the network, transport, session, and presentation layers are optional and are represented with different shading. However, some applications may utilize protocols implement the layers that exist above the AAL. For instance, existing Transmission Control Protocol/Internet Protocol (TCP/IP) applications can run over ATM-based networks that use the entire protocol stack. Below the network layer, device drivers for ATM network interface cards direct the variable length TCP/IP packets to the AAL, where they are segmented into 48 byte cell payloads, and sent through the ATM layer to the physical layer. When receiving ATM cells, the AAL reassembles the TCP/IP packets from one or more cells before the packet proceeds up through the IP stack.

ATM Technology. ATM technology is connection oriented, where network connections are simply logical *information* pipes of variable capacity with characteristics specified by the user application. It is assumed that cells arrive in the order sent. Isochronous constant bit rate (CBR) applications such as telephony or video have stringent requirements for end-to-end cell transmission delays and cell interarrival variability or jitter, and require assurances that adequate bandwidth will be available. To support isochronous data traffic in an asynchronous data stream, users can *reserve* a predetermined amount of bandwidth for an application. Some isochronous applications, such as variable bit rate (VBR) voice or adaptive compressed frame video images using Joint Photographic Experts Group (JPEG) compression or Motion Pictures Experts Group (MPEG) compression, generate data at a VBR, but the isochronous nature of the data requires that some fraction of the overall maximum bandwidth be reserved. Unused bandwidth is allocated to other network applications that do not reserve bandwidth because they require only best-effort service, or unused bandwidth can be allocated to other VBR network connections that, for a short period, require more bandwidth than had been reserved.

ATM cell streams are uniquely identified by VPI/VCI tuples so that several physical signals can be placed sequentially on a single physical media. Each cell carries an identifier, so it can be placed on the physical media asynchronously and any number of cells can be placed on the media as long as bandwidth reservations for the connection and physical limitations on bandwidth are observed. While

there is only a single data stream on the physical layer, users can think of dividing that stream into (virtual) bundles of (virtual) wires, an analog from the era when individual connections were carried over copper wire on a physical circuit. Because the only bandwidth limitations on the virtual wire are imposed when reserving bandwidth, any ATM cell stream could conceptually consume all available bandwidth on a physical link at any instant.

When there are several ATM cell streams being multiplexed over a single physical link, allocation of the bandwidth is performed statistically—according to guidelines defined as the user applications set up connections. Even with multiple user cell streams statistically multiplexed into a single transmitted data stream, each user cell stream must maintain its fundamental characteristics. CBR traffic must arrive with limits on the variability of the latency, as defined by the user. Cell latency is defined by propagation distance and processing delays through the communications network—factors that cannot be avoided. As long as delays have limited variability, or jitter, isochronous CBR signals can be transported over ATM networks with no degradation induced by the statistical multiplexing.

Statistical multiplexing can be contrasted with time-division multiplexing (TDM), where bandwidth is divided into discrete time slots that are assigned to a user for the duration of a call. Statistical multiplexing uses only the bandwidth required at any instant and ATM protocols permit users to obtain extra bandwidth as required for bursts of data; however, the potential for problems arise because of the possibility that jitter or variability could occur in the critical timing for isocronous data streams. On the other hand, TDM has typically been used to allocate bandwidth to various physical circuits simultaneously in previous generations of circuit switched communications equipment. For time-division multiplexed transmissions, it is simple to maintain constant latency by assigning adequate time-division slots to handle maximum anticipated bandwidth requirements. However, the link receives all bandwidth whether or not information is being transmitted in an assigned time slot, and there is no way to obtain additional bandwidth if there is a short-term requirement for sending bursts of data.

An important feature with ATM technology is the UNI and the NNI protocols. The ATM UNI/NNI protocols will provide fully automated network operations. User applications will request switched virtual circuits (SVCs) and will reserve required bandwidth automatically when connections are established. The ATM UNI/NNI protocol will also provide adequate intelligence within ATM switches to reroute network connections affected by link failures and to process requests for additional bandwidth on a connection. Implementations of the UNI/NNI conforming to the standards from CCITT and the ATM Forum, Q2931 and UNI V3.0, have begun to appear in production switches, and the standards-based UNI/NNIs are replacing propriety UNI/NNI implementations that have operated with great success on single-vendor networks for several years. Interoperable SVCs and a fully automated UNI/NNI will foster wide acceptance of ATM technology in both the military and the civilian community. Interoperable, fully automated SVCs combined with a capable network management system, should reduce staffing requirements for deployed ATM-based communications networks.

Priority is significant for military applications of ATM, because the requirement exists to replicate the concept of flash message traffic, a feature that cannot be adequately implemented with only the concept of reserved bandwidth. CLP is a single bit used to denote two classes of priority that determine which cells should be dropped when the switch encounters congestion. Development efforts at Rome Laboratory have demonstrated that it is possible to implement multiple levels of priority for a virtual circuit at the time the connection is established, but that feature is not currently part of the ATM specifications.

4. Tactical Military Applications and Implications

Current operations. Current US doctrine is predicated on a two-tier architecture for joint task force operations needed to cope with crisis events (Figure 3). This architecture is based on having a theater commander-in-chief (CINC) and his staff in a garrison location and the Joint Task Force Commander (CJTF), his staff, and the component elements deployed to a position in the combat area.

Anchor desks with access to large amounts of reference data and processed information regarding weather, logistics, intelligence, and other support functions will most likely be collocated with the CINC.

Presently, the deployed forces communicate with each other, and with the CINC, over dedicated circuits, usually either satellite, troposcatter, or HF radio (or public switched telephone networks if the infrastructure exists), but cooperative sharing of resources between users is often not practical because, for instance, while the weather and logistics channels are generally not only functionally separate, they are also usually physically distinct. Another example would be a video-teleconference circuit link between the CINC and CJTF which could not be shared with one of the force component commanders or be used for the exchange of imagery without changing the multiplexing plan. This diversity of applications and the lack of flexibility in using communications assets can result in the inefficient use of scarce resources.

The packet data networks are a different issue. Currently being put into tactical situations on a large scale, they allow several users to share common transmission resources which connect to other networks; new systems and standards improve interoperability and make messaging, electronic mail, and electronic file transfers simpler and more effective. Specifically, TCP/IP networks and emerging message standards are interoperable and utilize commercial hardware and software implementations—the major issue is one of system acquisition and compatibility of applications. And these systems are limited in their ability to accommodate isochronous traffic effectively (notably voice and video).

Future possibilities. The information from the anchor desks is to be disseminated to the task force either by "smart push" or "warrior pull" of the necessary data and imagery, and there is an increasing desire to have cooperation between military service components and between the CJTF and the CINC in the collaborative planning of operations. In practice, given the trends for tactical communications, the two-tier concept for a joint task force leads to the possibility of having parts of tactical units, such as an air operations center or a corps headquarters, interconnected by wide-band fiber optic cable to create "crystal islands" at forward locations; those islands themselves may be connected by constrained narrower bandwidth channels. This will permit units to move large amounts of data within themselves while passing smaller amounts to and from external sources. This results in the need for seamless communications between echelons and between forces across echelons as well as for common software applications on the workstations.

The capabilities of an ATM-based system facilitate this joint tactical force structure by permitting distributed collaborative planning among and between the JTF and CINC elements through the use of video teleconferencing, shared graphics, and shared databases. All units will be able to see a common tactical picture and respond to a common threat. This capability also suggests that not all support functions will have to be deployed to the battle area, that split-base concepts can be employed, and that resources can be used more efficiently. Some of the support personnel who might normally be deployed, and their computers, can be utilized at a distance—in effect, trading bandwidth for people on site. This virtual deployment would save money and time by reducing airlift requirements, reducing logistics in-theater, reducing force size, and reducing the planning cycle.

ATM permits these gains because the underlying protocols make more efficient use of the communications resources than is currently possible. The use of common communications resources in an ATM network allows users to request bandwidth-on-demand rather than have the fixed bandwidth assignment of the traditional stove-pipe systems; that means the detailed need-line analysis between specific points prior to deployment may be replaced by an analysis of aggregate bandwidth required. In addition, there is no longer a requirement for the reallocation of specific links as users come and go in the network. Finally, ATM makes common/interoperable command and control applications more valuable because the underlying communications are compatible.

5. Issues

All of the commercial ATM Broadband Integrated Services Data Network (BISDN) industry is based on compliance with accepted CCITT international standards as interpreted by the ATM Forum, a group of corporations and organizations involved in developing and marketing ATM products and services. As a result of this cooperation, there are several commercial vendors of ATM switches and interface cards, and commercial ATM service is about to emerge in the US and Europe.

This has facilitated the acceptance of ATM by the US military; the technology has already been demonstrated in exercises (Joint Warrior Interoperability Demonstration and Agile Provider). ATM technology has been included in testbeds (Joint Advanced Development Environment) and there has been tentative use in commercial service (MCI, NYNET, Sprint, Wiltel, Bell Atlantic, etc.).

Notwithstanding these achievements grounded on commercial systems and equipment, there are several tactical military-specific issues yet to be resolved before ATM service can be reliably extended to the theater; several of these considerations are discussed below.

ATM standards must be established for operation over disadvantaged tactical channels, including the probable need for military-specific forward error correction to reduce the effective error rate on noisy tactical channels. ATM was originally designed for use over optical fiber, a low-error-rate wideband transmission medium, but tactical communications are typically narrow-band high-error-rate channels which will affect the data payload more than the cell headers which have forward error correction coding required by the ATM standards. Since data payload errors will cause packet errors (if the transport layer protocol is the current military standard TCP/IP) which in turn will cause retransmission of packets, this problem has to be solved before the retransmission effects further reduce the amount of usable data on the link. Furthermore, ATM is not a reliable protocol like X.25 which guarantees delivery of the data and cells can be lost or corrupted without the source knowing about it. Some accommodations will have to be made in order to account for these effects and Rome Laboratory is pursuing alternative solutions to this problem.

There is also a requirement for a wideband, reliable communications infrastructure connecting tactical crystal islands. If the workstations at an air operations center are connected with fiber optic cables and are, therefore, capable of using ATM protocols for internal operations, it is important for those workstations to also be interoperable with workstations at the CINC and at wing operations centers at remote air bases. That implies the need for ATM connectivity over either satellite or troposcatter links.

In addition, since tactical units imply mobility, there is a requirement for a network management scheme which permits units to move from one hub/switch to another and which is not subject to compromise from external elements. To the degree that an air operations center will probably not move once it is in place (or at least it will not move often), it mimics normal commercial installations. But that relative stability isn't true of all Air Force units and it certainly isn't true for Army units, so the switch controllers and network managers have to be able to accommodate this volatility.

Similarly, commercial ATM networks are designed on the assumption that, given the bandwidth of the transmission media, there is no need for priority and precedence features in the protocols. Military networks, however, have historically had priority and precedence features, and the need for those features remains in a military ATM network with disadvantaged links that can only carry a limited amount of traffic between high-priority locations.

Security is another issue which has historically been significant in a military environment and that has recently been recognized as a problem in commercial networks as industrial organizations and financial institutions move large volumes of sensitive information in public networks. It will become even more important as the proprietary military networks fade and military information is transported over public networks. This implies a need for high-speed cell payload encryption devices, as opposed to bulk encryption, as well as assurance that the management information base

and the network management software are not exposed to possible exploitation.

6. Status

Some of the problems described above are being addressed in several efforts. First, the Air Force is completing the development of a concept model of an ATM-based tactical switch that will enable a wide variety of experiments on these issues. Called the Secure, Survivable Communications Network, or SSCN, it was built by GTE Corporation based upon their commercial product. Several features are provided by SSCN which were driven by the perceived military environment. These include; a modular interface to low rate channels down to 64 Kbps, interface to the TRI-TAC trunk rates, accountability of cells received with corrupted headers (for security reasons), and multiple levels of priority with preemption.

To enable a broader experimental program, Rome Laboratory in concert with other DOD services and agencies established a national level ATM test bed known as the Joint Advanced Demonstration Environment (JADE). From a communications perspective, JADE is a demonstration of military technologies, but it is also a means of connecting three service laboratories (Navy's NRaD, Army's CECOM, and Air Force's Rome Laboratory) so that command and control technologies under development can be made to interoperate on many levels. In addition to those laboratories, the following organizations are also part of JADE:

Defense Information Systems Agency's (DISA) Joint Interoperability Test Center (JITC), Ft. Huachuca, Arizona. Examples of all of the current tactical communications systems reside at the JTIC, and this enables experiments dealing with interfacing legacy systems;
Air Force C4 Agency (AFC4A), Scott AFB, Missouri where we will have access to the Air Mobility Command as a user;
480th Intelligence Group at Langley, AFB, Virginia (another user); and
Electronic System Center which is responsible for transitioning this technology into the field.

These nodes will be connected to several other facilities at Rome Lab, including facilities developing technologies for automated planning systems, providing access to and distribution of intelligence data, and a simulated, distributed Air Operations Center. At each site the communications capacities will be OC-3 rate, or 155 Mbps, and between sites we have leased 45 Mbps services from a US carrier; this provides a functional replication of a tactical deployment where units are connected internally with wideband fiber and then are connected to external elements by means of lower bandwidth circuits.

The potential JADE offers has received great interest within The Technical Cooperation Program (TTCP) forum which includes the United Kingdom, Canada, New Zealand, Australia, and the US. A plan is being developed whereby JADE will be extended to the Canadian Defence Research Establishment in Ottawa, Canada, the Defence Research Agency, Malvern, England, and the Defence Science and Technology Organization, Adelaide, Australia. The obvious benefit, other than that the research will demonstrate international communications interoperability, is the demonstration of interoperability among C2 technologies such as advanced planning systems. There is a great deal of collaborative work possible in getting ATM communications to the field but a great many technical challenges exist. Joint C2 is another area where work is needed and JADE has been postured to allow that to happen.

On a state-wide scale, a consortium of industrial research organizations and universities has been formed in New York State, for collaboration on research in applications enabled by the emergence of a future broadband communication infrastructure based on ATM. Under the sponsorship of NYNEX, the regional telephone service provider, a wide area experimental broadband communications testbed has been constructed in New York State. Utilizing fiber optic systems operating at rates as high as 2.4 Gb/s and the emerging asynchronous transfer mode switching technology, key universities, and research centers throughout the state are linked to this experimental network known as NYNET. Supporting the development of novel applications, NYNET is permitting new forms of research collaboration between academic and industrial groups.

Now fully operational, NYNET provides several important capabilities. First it provides remote access to high performance computers located at several major universities near Rome, NY as well as some other locations still being investigated. That access allows demonstration of the distribution of data fusion products coming out of distributed super computers, remote real-time simulation of missions, desktop video conferencing for collaborative battle planning and decision making, and access to high resolution imagery to support target planning and execution.

NYNET links Cornell, Syracuse, New York Polytechnic and Columbia Universities and the industrial research centers of Brookhaven Laboratories, Rome Laboratory, Cold Spring Harbor Research Laboratories, Grumman, and NYNEX together with NYSERNET. Initial applications planned involve innovative access to network resources to assist in economic development of small businesses, multimedia networks supporting concepts in the medical industry, and enhanced access to super-computing centers, thereby facilitating collaborative work between universities. Based on leading edge commercial service offerings, NYNET provides a prototypical model of the emerging broadband communications infrastructure. Providing a unique affiliation between a communications company, NYNEX, with other R&D organizations, applications can be better focused on a communication model that will become ubiquitous in the near future. Applications developed within this environment can be more readily transferred to industry as a result. In addition, as broadband commercial services offerings become more common, extensions of the network can be more easily planned. In fact, the potential exists to link NYNEX to some of the other nationwide testbed efforts already in progress.

NYNET provides an opportunity to stimulate work on emerging information infrastructure opportunities throughout the region and to form collaborative efforts among the research organizations. This sharing of research resources is expected to be a model of the coming information-based society of the future. Rome Laboratory will take a lead role in the development of a network management system for NYNET. As an R&D organization, not an operational carrier, Rome Laboratory has unique capabilities to support research in this area. Topics of interest will include: military to commercial network management interfaces and the use of artificial intelligence (AI) in automated network restoral.

In the United States, ATM technology is an emerging broadband switching technology being adopted by both the computer and communications industry. Representing a new approach to managing the transport of information across a network, ATM switching technology will equally support the transfer of voice, data, and video information. It represents a key technology in the paradigm of the future, commercial information infrastructure and, as part of the NYNET network, will permit development of a broad range of applications proposed for vertical industries such as medicine, education, finance, and small business development. The information infrastructure being stimulated at both industrial and federal levels is seen as a critical asset for future economic growth. Significant progress has been made in establishing the feasibility and in developing the network technology to support the communications infrastructure. Commercial companies such as NYNEX are beginning to deploy broadband network systems to support existing applications such as LAN interconnect. The future focus of research will be on new applications that will transform the way people work, are educated, or receive social services.

7. Conclusion

As ATM technology matures, it will provide a mechanism for implementing new command and control architectures and procedures. While the CINC's staff and the anchor desks will have fiber connectivity in the local enclave, they will also have more robust communications to strategic resources. This leads to the possibility of having centralized resources, and a wider range of resources, available to the CINC, and through the CINC to the CJTF and his staff. In fact, the specific geographic location of the data will be of decreasing importance as the communications become more capable.

The result will be improved collaborative planning efforts and improved techniques for information dissemination and distribution. The result will be reduced planning cycles and improved efficiency in the use of forces.

Also, since the CINC can also be connected to strategic resources and commanders, the line between tactical and strategic situations may also begin to blur and ultimately, the traditional command structure may be altered.

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