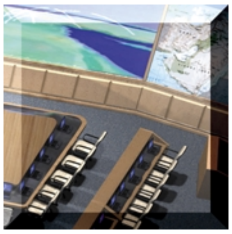


A Retrospective on Warfare Analysis at APL

Dale K. Pace and Russell E. Gingras

Developing a fundamental understanding of a problem is an integral part of APL's system engineering process. Since the 1940s, the Laboratory has used its warfare analysis capability to analyze military needs for the future, to evolve appropriate requirements to meet those needs, and to evaluate alternative solutions to meet those requirements. Information developed from APL warfare analysis contributed to important decisions which shaped our military forces. APL warfare analysis also contributed to the development of analytical tools and collaborative analysis techniques that have been widely shared and adapted within the defense analytical community. This article describes the origins and evolution of warfare analysis at the Laboratory and how it has been applied to a wide range of problems. (Keywords: Analysis techniques, Simulation, Warfare analysis, Wargaming.)

INTRODUCTION

Warfare analysis, the analysis of military forces for both peacetime and combat situations, has a long history and is very diverse. From ancient times, warfare analysis has helped military commanders determine how to fight, as indicated by Chinese military theorist Sun Tzu in *The Art of War* 2500 years ago: "With many calculations, one can win; with few one cannot. By this means I examine the situation and the outcome will be clearly apparent."[1] The use of war games with significant military detail began three centuries ago with *Koenigspiel* (the King's Game).[2] The rise of mathematically based natural sciences in the 17th century led to more quantitative methods in warfare analysis. British mathematician Frederick Lanchester developed equations to study World War I trench warfare by establishing quantitative relationships among unit quality, size, and the troop attrition rates resulting from confrontations with adversary units.[3]

The history of warfare analysis addressing "system" design also dates back to antiquity. Martin van Creveld[3] traces the adaptation of contemporary technology to warfare back to 2000 B.C. Such "analyses" led to the narrow entrances of Sumerian palaces so that only one person could pass at a time and to particular characteristics for Assyrian chariots and siege engines.[4] However, warfare analysis as a "systematic scrutiny in the spirit of science," and the use of its tools to address the operation of complex systems involving people are modern developments, dating back only to the mid-1930s.[5] Initial development of this approach to problem solving occurred in the operations research endeavors in England and the United States during World

War II, and became publicly available with the 1951 printing of the first textbook on operations research by two American World War II operations research leaders, Philip M. Morse and George E. Kimball.[6]

Warfare analysis at APL likewise has a long history and is diverse, addressing aspects of warfare ranging from campaign strategy to weapon system design. By far, the larger part of warfare analysis at APL has focused on weapon system design and modification. This article examines the beginning of warfare analysis at APL and aspects of its evolution (a full tracing of the subject is far beyond the scope of a single article), emphasizing both the Laboratory's contribution to warfare analysis methodology and insights from and consequences of the analyses.

Four primary considerations that are at the core of APL warfare analysis are explored:

1. *Logical soundness.* Is the analysis conceptually robust and adequate to address the issue? This involves both problem formulation and the analysis plan. Does the analysis plan address all viable alternatives? Or is it too narrowly focused to ensure the best result?
2. *Technical soundness.* Are the characteristics assumed for the systems correct? Do they come from theory, test, and operational experience? Are all data used in the analysis of the same type and credibility? GIGO, the acronym for "garbage in, garbage out," became a buzzword early in the computer era to help avoid overinfatuation with computational capabilities. The potential for such overinfatuation is even greater today when elaborate graphics associated with simulations can have such a strong emotional impact. If valid data do not drive the simulation, an impressive visualization of simulation results can lead to wrong conclusions. Valid and credible warfare analysis involves far more than merely selecting appropriate measures of effectiveness (such as kill probability) for a particular weapon system; it involves an understanding and appreciation of *all* technical and operational factors for which that measure of effectiveness is sensitive.
3. *Tactical and operational soundness.* Does the analytic process correctly represent the way that systems are likely to be used? Does it represent the way systems could be used? Has adequate input from experienced military personnel been obtained? An important part of tactical and operational soundness in analysis is the appropriate representation of adversary forces and actions. Representation of the threat in the analysis must be appropriate and characteristic of an adversary exhibiting capabilities and behavior that are responsive to our developments. APL maintains a close relationship with the defense intelligence agencies so that our analysts can use information in published intelligence sources properly. Laboratory personnel have, at times, assisted parts of the intelligence community in its technical analysis of foreign systems.
4. *Operational context.* Is the context rich enough to ensure that all relevant considerations are addressed? The *Aegis Threat Handbook* (which was developed concurrently with the Aegis System) was designed to ensure that all proposed modifications to the Aegis system were evaluated thoroughly by defining a baseline set of scenarios and operational situations that had to be assessed. That document evolved into the *AAW Threat Handbook* and stimulated similar threat handbooks for naval surface warfare and limited-warfare/low-intensity conflict (contingency operations). The emphasis on balance, scope, and comprehensiveness in warfare analysis is continuing today with the use of a littoral warfare handbook and Design Reference Missions (DRMs). These documents, all of which the Laboratory had major roles in developing for the Navy, characterize the principal factors that must be considered when evaluating proposed designs or modifications of specified weapon systems as well as when evaluating proposed changes in concepts of operation.

This article interweaves three themes. The first deals with methods of warfare analysis. The second addresses the kind of warfare analyzed, and the third looks at the level of warfare (weapon, combat system, unit, force) considered. Particular attention is given to warfare analysis during APL's first three decades, "the early years," and the endeavors of APL's Joint Warfare Analysis Department (JWAD) and its predecessor organizations. Table 1 illustrates some of the evolution of warfare analysis at APL in these areas.

THE FIRST THREE DECADES—THE EARLY YEARS

The Laboratory was established early in World War II, just 3 months after the attack on Pearl Harbor, to make practical a bold idea, the variable time (VT) proximity fuze for shells fired from shipboard antiaircraft guns. The VT fuze was an early precision weapon that greatly increased weapon effectiveness. In its initial application of shooting down aircraft, the VT fuze was 3 to 4 times more effective than time-fuzed shells and 50 times more effective than contact-fuzed projectiles.[7] General Patton lauded the effectiveness of the VT fuze: "The new shell with the funny fuze is devastating."[8]

During most of World War II, warfare analysis at APL focused on how to develop the VT fuze so that it would be reliable and effective, and on the APL-developed Mark 57 gun director to enhance its effectiveness in air defense.[8] For the first 2 years of their

Table 1. Examples from APL's warfare analysis evolution.

Decade	Initial application of techniques	Expansion in warfare analysis emphasis	Expansion in analysis scope/focus
1940s		Air defense	Weapons
1950s	Graphical analysis "Event-store" digital simulation	Strategic nuclear	Weapon systems Combat systems
1960s	Air Battle Analyzer Interactive graphical simulation	Anti-ship missile defense Undersea warfare Navy ballistic missile operations Strike and electronic warfare	Unit/platform
1970s	Interactive graphical simulation	Strike and electronic warfare	Battle group
1980s	WALEXs	Cruise missile defense	Multiwarfare missions
1990s	WALEXs with ESS Remote WALEXs Simulation credibility enhancement via VV&A Distributed simulation through HLA	Theater ballistic missile defense Unconventional warfare (terrorism and chemical/biological) Land warfare Information warfare	Joint force Coalition/allies
2000	WAL 2000		

Note: WALEX = Warfare Analysis Laboratory Exercise, ESS = electronic seminar support, VV&A = verification, validation, and accreditation, HLA = High Level Architecture.

combat use, proximity fuzes were restricted to at-sea application because

> The secret of their design was considered so crucial that they were banned from use over land, for fear that a dud might lead to enemy facsimiles or countermeasures. . . . [Even] the terms "influence" or "proximity" were classified, thus, the name variable-time (VT) fuze.[7]

After the veil of wartime secrecy was finally lifted, George Kistiakowsky of Harvard University, and later President Eisenhower's science adviser, noted that the development of the proximity fuze was second only to the atomic bomb in its contribution to winning the war.[9] By the end of World War II, a third of America's electronics industry was engaged in fuze work.[8]

Even before the end of the war, Navy leadership understood that gun-based air defense would be inadequate to cope with the evolving air and missile threat to the Fleet and tasked APL to develop a guided missile–based defensive system. Merle Tuve (APL's first Director) gave this project the code name "Bumblebee" in early 1945 because of a quotation that he had recently encountered: "According to recognized aerotechnical tests, the bumblebee cannot fly because of the shape and weight of his body in relation to the total wing area. But the bumblebee doesn't know this, so he goes ahead and flies anyway." "Bumblebee" seemed an apt, though somewhat ironic, moniker to characterize the daunting task that APL undertook in developing a missile-based air defense system.[8]

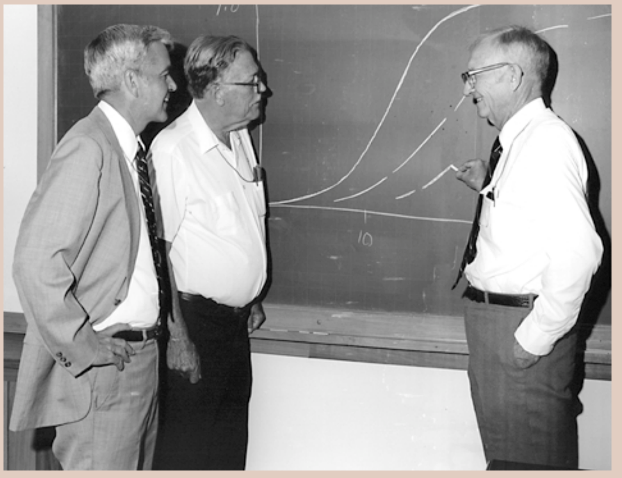
Warfare analysis at APL also expanded with movement into this new technical arena. It progressed beyond the issues of development and operation of the gun fire control director and the fuze. APL analyses began to address issues related to missile guidance and warhead lethality—the latter analyses ultimately led to development of the continuous rod warhead that was deployed on many Navy surface-to-air missiles (SAMs).[9] This expanded scope of warfare analysis caused the Laboratory to institutionalize part of its warfare analysis activities by establishing the Central Laboratory Assessment Group in October 1948 under J. Emory Cook, who was succeeded by A. George Carlton in 1949, and then by Charles F. Meyer in 1950. The group later became the Assessment Division, and was headed by Meyer until 1980 (see the boxed insert). Its primary purpose was to develop systematic studies that would enhance civilian developers' knowledge of military operators' needs regarding military requirements and weapons effectiveness.[11]

Graphical Analysis

During the early and mid-1950s, APL warfare analysis focused on the requirements and effectiveness of

DEVELOPMENT OF THE JOINT WARFARE ANALYSIS DEPARTMENT

In 1963, several members of APL's Central Assessment Division were asked to help the Laboratory's Fleet Systems Department (FSD) to establish an analysis group, headed by Richard J. Hunt, to focus on the needs of FSD. Much of the group's early work addressed missile system availability and helped the Navy to make significant improvements in that area through implementation of the Daily System Operational Test Program. An availability model developed by Hunt[10] showed how this approach would produce more substantial improvements in missile system availability than merely improving the reliability of individual components. The approach also helped to quantify the significance of the frequency and scope of the tests so that appropriate decisions could be made about them. Two years later, this analysis group officially detached itself from the Assessment Division and became a formal part of FSD.



Richard Hunt, Charles Meyer, and Alec Radcliffe (Assistant Supervisor of the Assessment Division) (left to right) discuss a distribution at the blackboard (circa 1970s).

In 1981, when Charles F. Meyer, Head of the Assessment Division, retired, the Assessment Division and the Fleet Systems Effectiveness Group merged to form the new Assessment Division under Hunt. Another merger occurred the following year when FSD's Systems Evaluations Branch, supervised by Robert F. Gehrke, merged with the new Assessment Division to become the Naval Warfare Analysis Department (NWAD). NWAD focused on applying technical intelligence to the systems engineering and operational employment of both aircraft combat systems and cruise missiles to defeat enemy air defense systems by tactics and countermeasures. It was first led by Hunt, and later by Gehrke after Hunt's retirement in 1992. NWAD addressed analysis as the basis for the specification of requirements and needs; analysis of systems, operations, and technical intelligence; development of tactics and countermeasures; and utilization of computer models and simulations.

As the result of a Laboratory reorganization in 1996, NWAD became the Joint Warfare Analysis Department (JWAD) to reflect its growing focus on the analysis of multiservice activities. The part of JWAD that focused on cruise missile analysis and airborne countermeasures tactics and requirements became part of the newly formed Power Projection Systems Department. Russell E. Gingras was appointed Head of JWAD in 1997 after Gehrke's retirement.

missile-based air defense, especially of naval units, i.e., AAW. These analyses addressed not only the Navy Terrier, Tartar, Talos, and Typhon missile systems, but also analyzed land-based Nike SAM systems. Initially, manual tactical simulations were employed, but their output was severely limited. For example, two good analyst-operators using a graphical aid such as the Terrier Tactical Simulator could only analyze about 10 iterations of a 30-target attack in a day. Such graphical devices supported the computation of SAM firepower.

In the latter half of the 1950s, findings from studies on search radar detection and tracking, fire control radar acquisition, launcher delays, missile trajectories, weapon delivery accuracy, and warhead damage were incorporated into these analytic methods as well. This approach to warfare analysis evolved into a kit of tools and methodologies that were made available to the Navy's warfare analysis community in the early 1960s. That kit, the Air Battle Analyzer (see Fig. 1),[12] forced a disciplined and systematic consideration of technical issues in the context of air battle geometry, timing, and possible tactics.[11] As such, the Air Battle Analyzer was the forerunner of the Warfare Analysis Laboratory (WAL).

Digital Simulations

As capabilities of digital computer systems increased, APL was at the forefront of developing computer simulations to support warfare analysis and was one of the first organizations to develop a major missile-based air defense computer simulation, which was programmed for a UNIVAC-1103 computer. That simulation was used to compare the effectiveness of Nike and Talos SAMs for defense of the continental United States. During the same period (mid-1950s), warfare analysis at APL addressed questions about potential Talos anti-ICBM capabilities and about the size (yield) needed for the Talos nuclear warhead. A new simulation, the Fleet Air Defense Simulation, was programmed for a UNIVAC-1103A in 1958, and later reprogrammed for an IBM-7090 computer.

The computer hardware and software limitations of the era required that a simulation be reprogrammed any

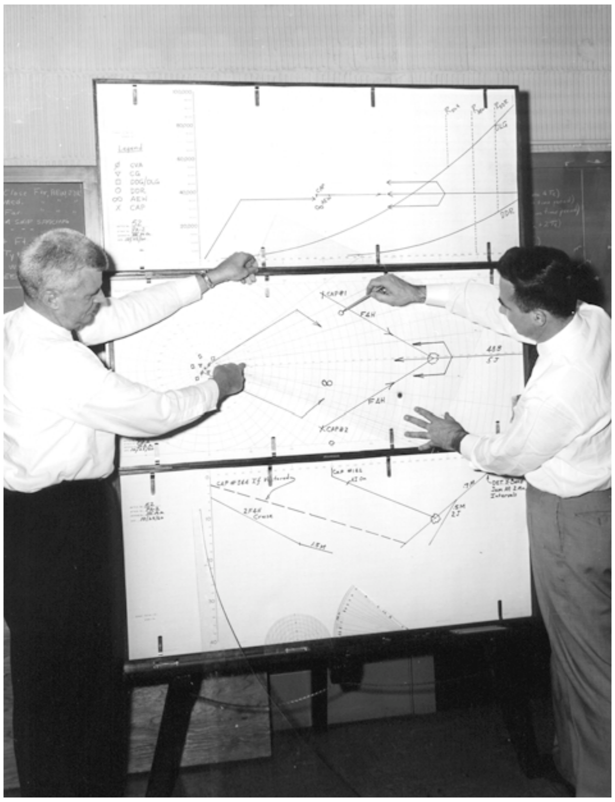


Figure 1. Stuart Ball (left) and John Long use Air Battle Analyzer nomographs to correlate horizontal, vertical, and time perspectives of a tactical situation (circa 1960).

time it was to be run on a different machine. This simulation was revised in 1961 and became the Fleet Anti-Air Wargame, a simulation with a sufficiently modular structure to allow repeated revision and continued use until the mid-1970s! Early on, these simulations were used to examine threat evaluation and weapon assignment doctrines. These analyses formed the foundation for doctrines used in ship-based air defense by Terrier, Tartar, and Talos SAMs in the Naval Tactical Data System and Weapon Direction System Mk 11.

During the 1950s and early 1960s, considerable effort had to be devoted to overcoming early computer limitations and extending the range of their applications. Internal storage constraints often required programming in assembly language. The rudimentary state of early operating systems frequently required the analyst/programmer to devise methods of connecting computer and peripheral equipment. Initial successes of these early warfare simulations resulted from using new machines (with their increased capabilities) and small teams that combined experienced analysts, who understood the key factors of the problem being addressed, and young professionals, who grappled with the software and hardware intricacies of those early computers.

At APL, the most successful teams often consisted of about six people. This size allowed the free flow of information and perspective among all team members. The team would spend about 2 years producing and checking a program of 20,000 machine instructions. As more capable machines became available, high-level computer languages were used for warfare analysis simulations. However, the time required to construct the simulations was not reduced noticeably because the models used within them became larger and addressed more factors than in previous simulations. Because major simulations always require substantial effort to develop, they are often built on the thinking and sometimes the code of previous ones. The challenge for the warfare analyst is to ensure that the reused ideas and code are appropriate for the new application because inappropriate reuse of existing software can have catastrophic consequences (as happened with the Ariane 5 disaster).[13]

APL was an early leader not only in the development and uses of warfare analysis simulations but also in the development of analytic and programming methodology for computer simulations. It is often difficult to determine where a particular technique was first employed because similar development activities were proceeding rapidly at several organizations simultaneously, such as at the Rand Corporation and the Center for Naval Analyses as well as at APL. In addition, interactions among staff members of these organizations at meetings of the Military Operations Research Society, Society for Computer Simulation, and similar professional societies, as well as during the performance of multiorganizational tasks for DoD, allowed sharing of ideas, which facilitated development of methods and capabilities at all of the organizations. Also, in many cases, the classified nature of the work prevented general publication about methods and simulations at the time of their initial application.

Some of APL's early digital computer simulation analytic and programming techniques, i.e., those of the 1950s and 1960s, included the following:

- The Event-Store Technique for simulation time management[14]
- Use of random walks to simulate underwater sound conditions
- Development of packages of subroutines for geometry, kinematics, and detection in FORTRAN and PL/1 to simplify and unify the construction of computer-supported wargames
- Use of methods to separate the decision logic from computations in complex simulations
- Interactive, graphical simulation of naval warfare
- Use of simulation results for preprocessing data for Fleet exercise critiques and for assessment of other simulations

Table 2 identifies the kinds of warfare analysis simulations that APL was the first or among the first to develop. Many of the warfare analyses during those years, both at APL and elsewhere, were possible owing to these developments.

Expansion Beyond Air Defense

In 1957, APL became involved in an analysis of possible roles for Navy aircraft in a strategic (nuclear) war with the Soviet Union and its allies (Project Tau). In 1958, APL became an initial participant of the Navy's War Games Project that included the Naval War College, Naval Electronic Warfare Simulator, and Naval Weapons Laboratory. APL's role was to construct models in naval strike warfare, antisubmarine warfare (ASW), anti-air warfare (AAW), and limited warfare to examine the Navy's role in strategic warfare. These models became feasible because of the recently developed Event-Store Technique for managing simulation time and sequence of events, which provided a new and powerful method for describing the complex interactions of events in naval tactics. APL support of Navy strategic warfare analyses continued for many years.

In 1965, because of its understanding of SAM systems, APL was asked to participate in Project F/O 210, an endeavor that analyzed U.S. aircraft losses and developed tactics and techniques to counter North Vietnamese air defenses. Four years later, APL was invited to the first conference on requirements and tactics for the EA-6B, the Navy's jamming aircraft, and soon was tasked with developing requirements and tactics for Navy airborne jamming systems, a responsibility that continues today. In the mid-1970s, the Air Force asked APL to help with requirements and tactics for the EF-111A, the Air Force's jamming aircraft. The participation of APL personnel and military operators in tests as well as theory is one of the ways in which the Laboratory ensures that its warfare analysis is tactically and operationally sound as well as technically correct and logically robust.

Table 2. Large computer simulations developed at APL believed to be the first of their type.

Year	Computer simulation
1957	Shipborne AAW and land-based air defense
1959	Submarine and air barrier operations
1959	Naval air strike operations
1961	ASW localization and kill
1962	Submarine detection and localization SOSUS/patrol aircraft
1963	Submarine approach and attack
1966	Submarine training
1968	Interactive computer-supported war game

Note: SOSUS = Sound Surveillance System.

High-Fidelity Engineering Simulations

Since the 1960s, warfare analysis at APL has become increasingly more diverse. Individual programs and departments have performed detailed engineering analyses for specific systems to enhance the quality of the systems' design, to determine how best to use them, and to establish their effectiveness. These efforts have included specialized simulation facilities such as the Guidance System Evaluation Laboratory, a hardware-in-the-loop facility to examine missile guidance issues using missile seeker hardware, and the Submarine Combat Information Laboratory, a mock-up of a submarine command center used to evaluate a number of operational issues. Other engineering analyses addressed how to combine test and simulation results to achieve a specified level of confidence in performance from a minimum number of submarine-launched ballistic missile flight tests.

Visualization

In 1968, a computerized extension of the Air Battle Analyzer, known as Tactical Analysis Digital Simulation (TADS), was completed. TADS allowed the human decision processes of the Air Battle Analyzer to be combined with the presentation of formatted data that simulated an operation likely to be encountered by personnel. In order to implement the interactive nature of TADS, the simulation was developed to run on the computer and display equipment used in a shipboard combat information center. TADS was used in evaluations of what later became the Aegis SPY-1 radar and in evaluations of large-screen displays for AAW commanders on Aegis ships.

APL developed similar graphical, interactive simulations for ASW applications, including the Antisubmarine Graphic Allocation Model designed to represent allocation of ASW patrol aircraft and ships against hostile submarines, the War at Sea Graphical Analysis Model adopted by the U.S. Naval Academy in the late 1970s as a training device, and the Localization and Tracking ASW Model. Although today graphic simulations are commonplace, in the late 1960s and early 1970s, they were rare.

FROM INDIVIDUAL SYSTEM DESIGN TO FORCE-LEVEL OPERATIONS

APL conducted warfare analyses, sometimes with other organizations, that identified paths for correcting problems with deployed weapon systems and defined characteristics required for future generations of weapon systems. These analyses also established the effectiveness of individual systems alone and in combination with other systems in a military force. In the early 1960s, the 3T Get Well Program addressed the transformation of the Terrier, Tartar, and Talos radars, launchers, interceptor missiles, and weapon control capabilities into reliable and effective defensive systems. The 1965 Advanced Surface Missile System Study, also known as the Withington Study, analyzed and defined weapon system characteristics that would be specified later in the 1972 contract for the Aegis weapon system (which entered the Fleet on the first Aegis cruiser in 1982).

AAW coordination analyses of the mid- and late 1970s identified not only the Fleet air defense limitations imposed by the contemporary naval data link (Link 11), but also those limitations that could be expected with the next-generation data link, the Link 16 Joint Tactical Information Distribution Systems (JTIDS). These studies determined the increase in effectiveness resulting from fuller AAW coordination and provided impetus for what was originally called the Battle Group AAW Coordination Program, which later became the Cooperative Engagement Capability.[15,16] In the 1980s and 1990s, assessments of AAW coordination became much more sophisticated with higher-fidelity representation of communications, doctrine, radar functions, etc., in engagement simulations. This capability allowed more realistic assessment of the potential benefit from force-level coordination and enhanced the capability to assess coordination of the various weapons used in ship self-defense. As a result of these assessments, high-energy laser systems were added to the list of possible weapons in the AAW suite along with missiles, guns, and electronic countermeasures.

From the 1960s through the 1990s, APL continued its warfare analysis interactions with other parts of the defense community, especially with elements of the Navy. The Laboratory was often involved in multiorganizational studies, and sometimes exchanged simulations with other organizations. One simulation import was the Force Level Operational Analysis and Tactical Simulation from the Center for Naval Analyses in the early 1970s. APL modified this simulation and used it in warfare analyses for more than a decade to evaluate candidate AAW systems for the FFG 7 guided missile frigates, Tartar destroyers, New Threat Upgrade Terrier cruisers, and the DDX class of guided missile destroyers (later called the Aegis DDG 51 class).

Other imported simulations were the Maritime Anti-Ship Tactics and Multi-Battlefield Engagement and Reaction (MBER) simulations (from Kamak Corporation in the mid-1980s). The Laboratory significantly modified them and used them for cruise missile programs analysis during the 1980s and 1990s. A more recent example of a simulation import is the Extended Air Defense Simulation, developed and managed by Teledyne Brown Engineering, which APL and others are using in air and missile defense analyses.

The Relative Contribution Model (RCM) was one of the simulations that the Laboratory exported to other organizations. It went to the Naval Ship Weapon System Engineering Station and to the Naval Weapons Center at China Lake, California, in the early 1970s. RCM was an early example of simulation portability, i.e., a simulation that could be run on a variety of computer platforms and used by different organizations. The model was designed to provide insight about the relative contribution of soft-kill weapons (such as jamming and chaff) and hard-kill weapons (like guns and missiles) to ship defense against anti-ship cruise missiles. It was used extensively in the 1972 and 1975 Anti-Ship Missile Defense Analytic Assessment Program studies. Sometimes simulations exported from the Laboratory were the modified and updated versions of simulations that had originated elsewhere, such as the APL-MBER simulation (derived from MBER mentioned earlier). In the mid-1990s, APL-MBER became the Navy's community-approved Tomahawk Effectiveness Model.

BATTLE AND WARFARE ANALYSIS TECHNIQUES AND ACTIVITIES

Evolution of the WALEX

The disciplined consideration of technical aspects of a warfare problem, along with the geometry, timing, and possible tactics embodied in the warfare analysis process that characterized the Air Battle Analyzer, was carried a step further in the early 1980s when APL established the WAL. It was designed to facilitate the warfare analysis process with display capabilities, simulation support, and data recording capabilities.

The warfare analysis process using the WAL, called a WALEX for Warfare Analysis Laboratory Exercise, has been applied to a wide variety of warfare problems. Some WALEXs are in-depth engineering examinations, e.g., the early 1980s exploration of appropriate "if-then" logic for Aegis Doctrine Management Systems when multiple Aegis ships were deployed together, and the mid-1990s Air-Directed SAM WALEXs (see the article by Kauderer, this issue). Other WALEXs are senior policy–level assessments of issues, e.g., the late 1980s WALEXs that played a central role in establishing the potential effectiveness of antisatellite system candidates and in building consensus as to program need.[17] A similar WALEX in the mid-1990s discussed Theater Missile Defense acquisition policy issues for the Under Secretary of Defense for Acquisition and Technology, the

Ballistic Missile Defense Organization Director, and other senior defense officials of the United States and its NATO allies. Topics addressed in WALEXs can be warfare-related (such as weapon and technology proliferation); however, nonmilitary problems (such as transportation issues for advanced highway systems) have also been analyzed.

The capabilities of the WAL have been enlarged to support the needs of increased sophistication in warfare analysis. The original WAL had a single large-screen display tied to a limited computer suite. The current WAL configuration has four large-screen displays and flexible video switching that allows the displays to be driven not only by simulations, databases, and other information on any computer within the WAL, but also by remote computers that can be accessed via various means. This kind of capability facilitates more high-fidelity examination of complex issues than may be possible otherwise. Appropriate and timely displays are also very valuable in creating a common frame of reference for WALEX participants, which helps to ensure that the more significant issues of a problem are addressed and that disputes that might otherwise impede progress in solving problems can be settled.

APL was an early leader not only in the development and uses of warfare analysis simulations but also in the development of analytic and programming methodology for computer simulations.

Although electronic group decision support systems have been used to assist business management activities since the late 1980s,[18] APL became one of the first organizations to employ such technology in defense warfare analyses with the installation of a group decision support system in the WAL in 1992. The system allowed more complete data collection during WALEXs and facilitated multiple, simultaneous discussions among WALEX participants by allowing electronic communication to supplement verbal communication. Individual participants could ensure that their ideas were captured correctly since they could input them into the WALEX record directly. Because participants were stimulated and enlightened during the WALEX by comments from others in the group decision support system, the intellectual content of the exercise was enriched. In addition, the system enabled greater use of techniques (voting tools, analytic hierarchy methods, etc.) that allowed all WALEX participants to simultaneously evaluate alternatives against multiple criteria. The first application of such a group decision system to support DoD's Program Planning Budget System process was the 1992 Navy Flag Level Joint Mission Area Assessment, which used the WAL's Electronic Seminar Support System, a commercial group decision system.

APL helps others understand this kind of collaborative warfare analysis through publications available to the community.[19–21] The defense community's broad participation in WALEXs increases the understanding of this approach to warfare analysis as well. In addition to WALEXs at APL, since the mid-1990s APL warfare analysts have led seminar games (called "WALEXs" because of their methodology and their use of a portable group decision support system) at a number of locations in the United States (e.g., Pacific Command, Atlantic Command, Joint National Test Facility, and the Pentagon) and abroad (e.g., NATO Headquarters and what was formerly the Supreme Headquarters Allied Powers Europe [SHAPE] Technical Center). In the 1980s and 1990s, APL provided training in this methodology for analysts from other organizations and shared insights about the WAL with others who built wargaming and decision support facilities of their own, drawing on the experience and design of the WAL.

Increased Simulation Capabilities

Dramatically increased computational capabilities in the 1990s enabled computer simulation to advance far beyond past capabilities. Warfare analyses using extensive simulation could consider many more parameters than was possible in the 1960s through the 1980s. However, although more relevant factors could be addressed, analysts could lose sight of driving issues and focus on mere computation. Throughout this decade, APL analysts were developing analysis methodology directly related to the issue of increased simulation capabilities by providing theoretical and practical help in simulation verification, validation, and accreditation (VV&A). VV&A is the key to simulation correctness and credibility. APL personnel have contributed to Navy, National Security Agency, and other defense VV&A policy development efforts, have published extensively about it, and are providing VV&A leadership in a number of areas.

As computational capabilities increased, warfare analysts were expected to put their findings in more extensive contexts than had been required before. This expectation led to three new areas of emphasis within the Joint Warfare Analysis Department during the mid- and late 1990s: simulation-based acquisition, affordability (especially as it pertains to weapon system acquisition decisions), and the linkage of warfighting and logistics. In the past, APL warfare analyses focused mainly on system requirements, performance, and capability. These efforts addressed system reliability and availability, but largely left consideration of logistics to others. In 1997, APL began the Warfighting and Logistics Technology and Assessment Project to demonstrate the feasibility of linking legacy logistics and warfighting models to study their interrelationship.

Topic and Issue Comprehension

A fundamental premise of warfare analysis at APL is that a complete understanding of the issues by the analysts is essential for good analysis. Otherwise, the problem may be formulated inappropriately, critical issues may be neglected, and conclusions may be reached that do not have the desired logical and factual robustness. APL warfare analysts address the subject of issue comprehension in a variety of ways, three of which are discussed briefly below: use of "war rooms," Infosphere considerations, and human behavior and decision making.

War Rooms

The use of war rooms is a technique that APL employs to develop appropriate understanding of a topic so that subsequent analyses related to that topic have the needed depth, breadth, and perspective. During the 1990s, the Warfare Analysis Department established war rooms for this purpose on combating terrorism, network-centric warfare, joint warfighting requirements, theater missile defense, strike warfare, and small-scale contingencies. This approach was also applied to APL's comprehensive strategic planning activity in 1998 in analyzing the external business environment and its implications for the Laboratory. A war room was assembled to cover future world situations, potential threats, fiscal trends, expected technology advances, and the changing acquisition environment. From the analysis, APL identified several new strategic initiatives to pursue, including counterproliferation, information operations, commercial space, and law enforcement.

Infosphere Considerations

Information operations, information warfare, and network-centric warfare are buzzwords found frequently throughout contemporary defense analyses. They indicate that future warfare analysis will have to address information aspects of warfare more completely than in the past. The Joint Warfare Analysis Department has undertaken a number of initiatives to help the Laboratory and its sponsors consider implications of advances in information, communication, and networking technology for military operations, defense community organizations, and society.

One of these initiatives was the Infosphere Seminar Project. "Infosphere" refers to the fusion of the world's communications networks, databases, and other sources of information into a vast, intertwined, and heterogeneous tapestry of electronic interchange. The global fusion of networks changes the character of each individual network. Networks will no longer serve simply as the medium through which people in different places can communicate, enhancing their *in situ* activities. The global fusion of networks creates a network ecology—literally, a place in which people can gather and do business. People will be able to conduct their activities increasingly in the global network ecology, the Infosphere.

The Infosphere Seminar Project began in 1997 with a seminar for APL leadership, followed by a seminar for APL cyber specialists. The possible impacts of the Infosphere (not only information warfare issues) on military operations and organizational structures were explored. These seminars provided a number of insights, both about military operations and about APL's own functioning. They underscored the importance of working in an Infosphere environment. An Infosphere-engaged workforce, deft leadership, and Infosphere compatibility in policies, organization, and environment are important for effective and productive organizations in the defense community.

APL shared insights from these seminars through conferences at the Naval War College and the Joint National Test Facility, and through a widely distributed paper, *The Navy and the Infosphere*.[22] APL started a series of Cyber Tech Seminars during 1998, in which leaders from various cutting-edge information enterprises shared their visions of the future in public forums and discussed their implications with their peers.[22] Endeavors such as the Infosphere and Cyber Tech Seminars are examples of ways that APL warfare analysts develop a more complete understanding of issues related to the problems they address.

The Human Factor

More complete representation of the information aspects of warfare must also include the way that human behavior and decision making are represented in warfare analysis. The likelihood of correct choices, factors that determine choices, times to reach decisions, etc., must be represented more explicitly than in the past. As pointed out by APL warfare analysts, it is not enough simply to ensure that the model used in the analysis fully addresses the network-centric warfare flow of information through communication channels and displays. "The human is the governing factor in total information dominance and network-centric warfare."[23] This was an important perspective of the Laboratory's work in the late 1990s for the Marine Corps relative to maneuver warfare, a perspective which is now being incorporated in the next generation of land warfare models.

Attention to "Neglected" Topics

In a 1989 meeting at APL, the President of The Johns Hopkins University raised a question about whether adequate attention was being given to the non-Soviet submarine threat. A team within the Warfare Analysis Department was assigned to examine this issue. Was the non-Soviet "rest of the world" submarine threat basically a lesser included case? Or was it sufficiently different and threatening to warrant special consideration on its own? The conclusion: adequate response to the "rest of the world" submarine threat would not be a fallout of the U.S. Navy program to counter the Soviet threat. The analysis was sufficiently convincing that the Director of the ASW Division in the Chief of Naval Operations Naval Warfare Directorate began a campaign for recognition of this danger. That campaign included an article in the *U.S. Naval Institute Proceedings*[24] and briefings to the Secretary of the Navy and the Vice Chief of Naval Operations, with the result that significant attention is now being given to Third World ASW, especially to submarines.

Pushing for Novel Capabilities

In 1996, APL led the multiorganizational Cost and Operational Effectiveness Analysis for the Long-Term Mine Reconnaissance System. This analysis was able to define a system capable of being launched from a submarine torpedo tube that would have adequate range and capability (including reliable autonomous behavior) to satisfy the stringent system requirements. The Navy Unmanned Underwater Vehicle Program Manager was confident enough in this approach that he proceeded with system development for deployment early in the next decade.

CURRENT TRENDS AND FUTURE CHALLENGES

In the decade from the mid-1980s to the mid-1990s, there was growing emphasis on the analysis of naval forces in multiwarfare and in Joint force contexts. These trends required that APL warfare analysis address issues with more sophistication. The role of space and its impact on warfare as well as theater ballistic missiles and defense against them were also given more attention. Toward the end of this period (i.e., the mid-1990s), more analysis was devoted to what has come to be called information operations and information warfare, as well as ways to properly represent them in warfare analysis.

Four major challenges confront future warfare analysis:

1. Problems have become more difficult to analyze because they involve situations (e.g., conflict in urban environments and the need to minimize collateral damage, military operations other than war, and information operations and warfare) for which existing analytic techniques are not as mature as those applied to other topics (e.g., traditional air defense or blue water AAW). There are also more stringent demands on system designs, such as those required by hit-to-kill missile defense systems (compared to the demands of system designs for traditional SAM systems), which require more accurate and precise analytic techniques than in the past in order to provide guidance with acceptable levels of technical risk.
2. Expectations have become higher. Many sponsors, military commanders, and defense leaders expect simulations and other analysis tools to be interoperable and capable of supporting integrated, collaborative analysis. They all want high-quality analyses immediately and cheaply.
3. Temptations are greater than ever merely to please consumers of analysis, especially with sophisticated graphics and animation, without providing adequate attention to real issues and facts. It is too easy to retreat to an emphasis on process when grappling with an important, yet difficult, complex, and intractable problem, instead of focusing on developing a real solution to it.
4. Analytic stakes are higher. Fewer defense dollars are available, both for forces and for analysis. Thus, it is imperative to get correct answers, to ensure that there are no fatal flaws in military capabilities, and to do this with fewer resources for analysis.

CONCLUSIONS

Examples of the breadth and depth of warfare analysis at APL and how the Laboratory has contributed to advances in analytic capabilities within the defense community were examined in this article. Whereas many important topics were mentioned only briefly here because of space limitations, other articles in this issue provide substantial descriptions, insights, and methodologies of specific, current APL analyses. APL analysts continue to develop innovative warfare analysis techniques and tools needed to provide defense decision makers with information and insights about the increasingly complex problems associated with defense systems.

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