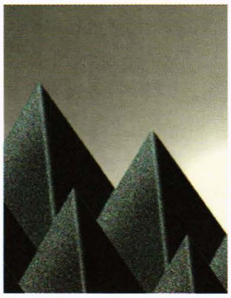

Combat System Effectiveness Modeling to Support the Development of Anti-Air Warfare Tactics

Scott A. Hyer, Jerald J. Johnston, and Charles L. Roe

The Applied Physics Laboratory is working with Navy planners to provide solutions for protection of the Fleet in challenging threat environments. Integrated models of sensors, command/control elements, and engagement assets are used to predict the performance of shipboard combat systems and assess overall effectiveness against postulated threats. Results from these studies help policy makers devise methods for employing weapons, assigning assets, spacing firings, and coordinating hardkill/softkill engagements. Guidance is provided to Fleet units in the form of tactical memoranda and tactical notices, which advise commanders on the optimum use of equipment under their command in various combat situations.

INTRODUCTION

Naval ships must defend themselves against advanced airborne threats characterized by high speeds, low approach altitudes or steep dive trajectories, maneuverability, and the ability to deceive defensive systems using countermeasures.[1] Concurrently, they must contend with environments that may include enemy jamming of radars, atmospheric factors that affect sensors and weapons in unpredictable ways, and inadvertent interference to sensors from the emissions of other ships. Figure 1 illustrates the context for anti-air warfare (AAW). Ship defense presents a significant challenge to the operator who must respond while complying with complex rules of engagement. To make the task reasonable and manageable, the operator must have tactical guidance that allows the ship's command to tailor combat system responses in accordance with established doctrine.

Tactics are developed through a detailed assessment of combat system performance in tactically realistic scenarios. Although some data are available from Fleet exercises and land-based testing, integrated combat system models are a primary source of data for assessing system performance, especially for the most stressing threats and in the highly complex environments that are difficult to achieve in actual at-sea testing. As funding becomes more constrained, the use of costly at-sea testing is likely to be reduced, and modeling will become even more important in the development, testing, and approval of tactical doctrine.

To assist Navy planners in the enhancement of Fleet readiness, APL has developed and integrated large-scale combat system simulations to study problems of man–machine interaction, the consequences of employment of combat system assets in specific ways to counter stressing threat scenarios, and enhanced approaches to employment strategies. Results from these simulations and analyses also assist planners in making weapon system procurement and upgrade decisions, and support the development of Navy tactics and policy.

THE ANALYTICAL PROCESS

The analytical process begins with establishing specific objectives for the analysis. This involves more than determining what knowledge is to be provided by the analysis. An objective aimed at improving system performance through the implementation of doctrine or tactics would likely require a very different analysis than one to support a procurement or system upgrade decision. The former may require detailed modeling of the system being considered, whereas the latter might be done with a generic model, as long as modeling assumptions were consistent so that results could be meaningfully compared. Figure 2 illustrates the analytical process for the computer modeling and simulation of combat systems.

The second step in the analytical process is to identify the appropriate system measurables. If the objective is to establish tactics and doctrine, the analysis must be based on meaningful real-world measurables. It makes no sense to attempt to establish doctrine based on target characteristics that are not physically measurable by ship systems or on factors that cannot be reliably predicted.

Study objectives often depend on what the critical measurables of the system are. For AAW, these include the range at which an anti-ship missile could be tracked, the time required for the system to react to the threat after a track is established, the spacing between successive firings of a ship's defensive missile, or the engagement capabilities of a ship's gun system. The critical measurables selected for the analysis of a system

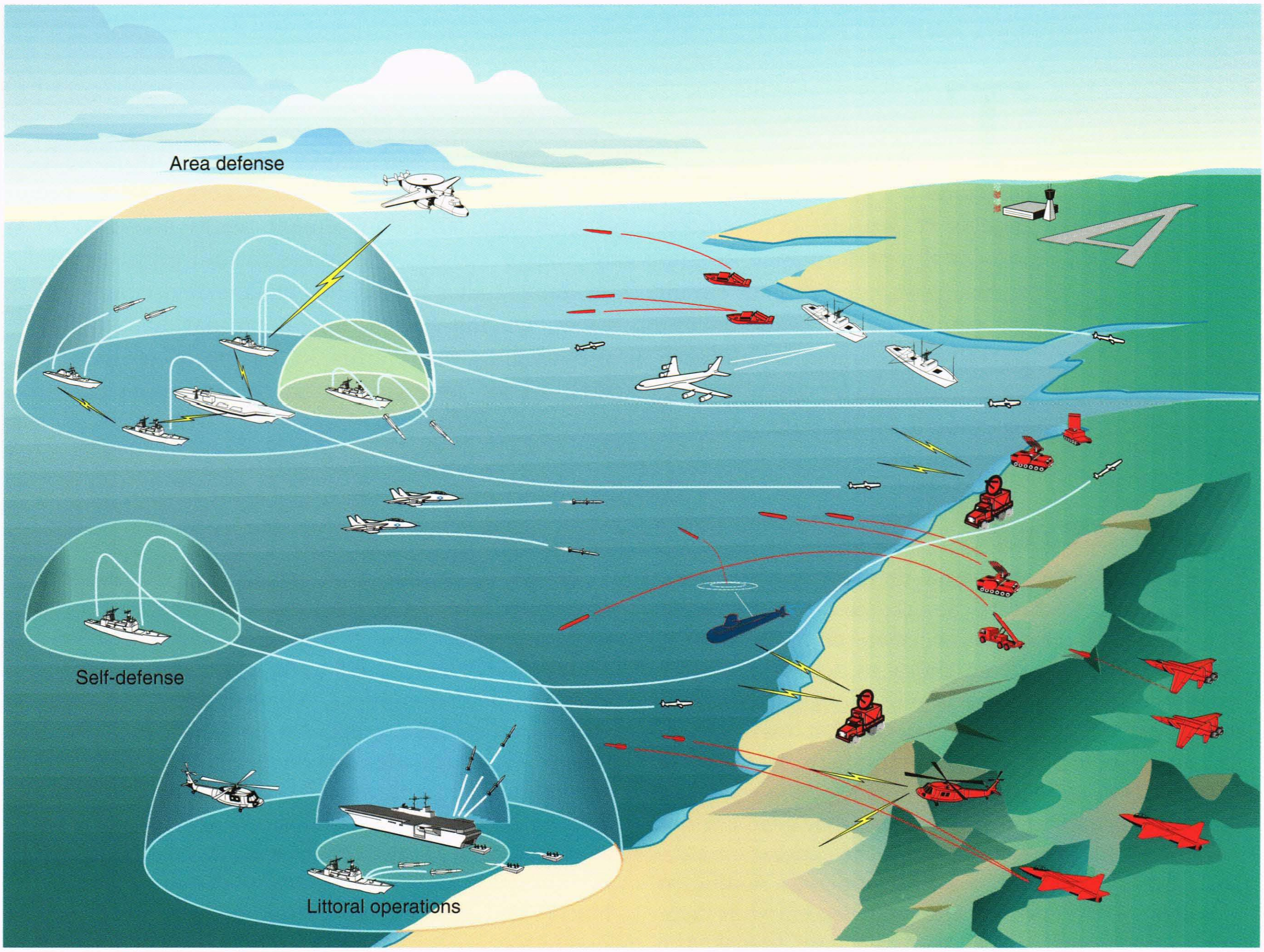

Figure 1. Operational tactics of Navy ships must take into account complex environmental factors as well as stressing threats. Operations near land, as shown here, must contend with land clutter and limited warning time of threats. Complex identification of friend and foe may be further exacerbated by constraining rules of engagement. An intense electromagnetic interference environment may result from the combined operations of friendly forces as well as enemy jamming of sensors and weapons. The threat may consist of combined sea-skimming and steeply diving hazards in high numbers, with sustained attacks over a prolonged period.

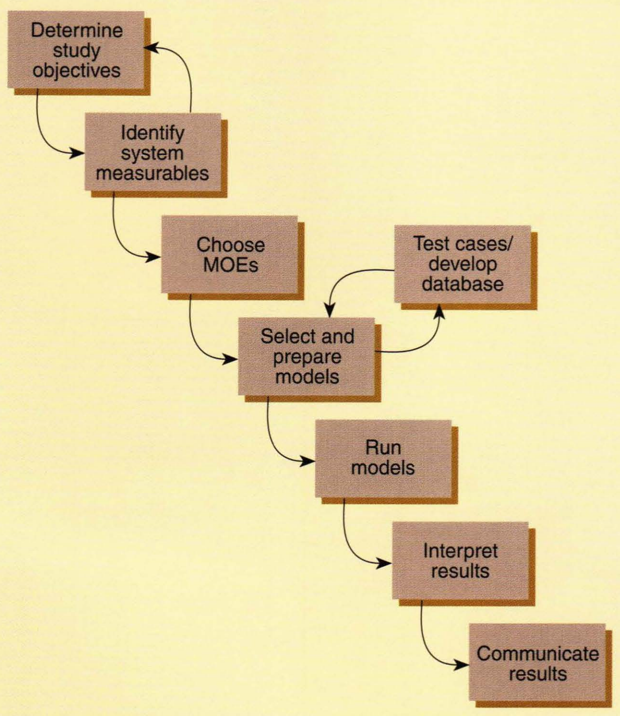

Figure 2. The analytical process for modeling and computer simulation of combat systems to support tactics development follows a logical and disciplined methodology. Beginning with a clear formulation of goals and objectives, models and simulations are chosen that will produce the information needed by the analyst to develop results and conclusions. (MOEs = measures of effectiveness.)

depend extensively on the goals of the analysis, yet limits on possible measurables can require adjustment of the analysis objectives. The steps in the analytical process are therefore iterative. Systems analysts resolve these issues on the basis of their experience and knowledge of the system.

As goals and critical measurables become fixed, measures of effectiveness (MOEs) for system performance are selected and used to evaluate the overall objectives of the analysis relative to the critical measurables. Typical MOEs for AAW are the amount of ordnance that would be expended in a given defensive engagement, the number of anti-ship missiles that would be defeated, and the probability that the defended ship would survive or escape significant hit by an anti-ship missile.

Once objectives, critical measurables, and MOEs have been determined, one or more appropriate models are selected for the analysis. These may range from simple computations or computational procedures to stochastic simulations of the system operation. Often the models must be modified, especially to incorporate the proposed tactics under evaluation. The models involved in the analysis must be integrated into a framework that provides a valid system representation. An essential part of the modeling is to check the models with known test cases to establish confidence in the results. At this point the analytical process has just begun. Modeling involves more than merely producing numerical results. The modeling process must be monitored constantly, and results must be checked, trends examined, problems identified, and answers produced that address established objectives.

Although the cost of operating simulations is modest compared with the cost of obtaining empirical data from field tests, the shear numbers of cases that often need to be run can easily drive costs beyond the intended scope of an analysis. Thus, the cases to be run must be selected judiciously. The number of cases often can be reduced by careful planning at the start of the analysis. Intelligent partitioning of the cases into sets can help reduce the number if the partitioning is done such that superfluous cases become evident after running just a few sets. Test cases are important to ensure that the simulation results will be useful in addressing the analysis objectives. Problems with the model or the parameters selected for the simulation can be identified, thereby saving time and computer resources.

Interpretation and communication of the results are the final phases of the analytical process. Interpretation can be summarized as deducing the consequences of the analytical process for the systems analyzed and the tactics and doctrine they suggest. The assumptions and limitations inherent in the analysis must be understood.[2] Communication of analytical results involves presenting both interpretations from the analytical process and the implications of the results for real systems.

CHARACTERIZATION OF COMBAT SYSTEMS

The combat system is characterized by specifying functionality and parameters as inputs to the models. These inputs form a database. Figure 2 shows this critical step in the analytical process as preparing the model and developing the database. Figure 3 illustrates some of the detect, control, and engage subsystems of a combat system that are specified. Some characteristics are well known and controllable, whereas others are highly variable and hard to define precisely. Dynamic characteristics are best modeled by using statistical distributions of the parameter values or by parametric analysis. The statistical randomization of a parameter models a system characteristic that is unpredictable at any instant in time, but whose statistical behavior over time is known. Parametric analysis consists of determining subsystem performance while a parameter is varied over its range of possibilities. The resulting function can then be consulted as the model is run. Detect, control, and engage subsystems are used

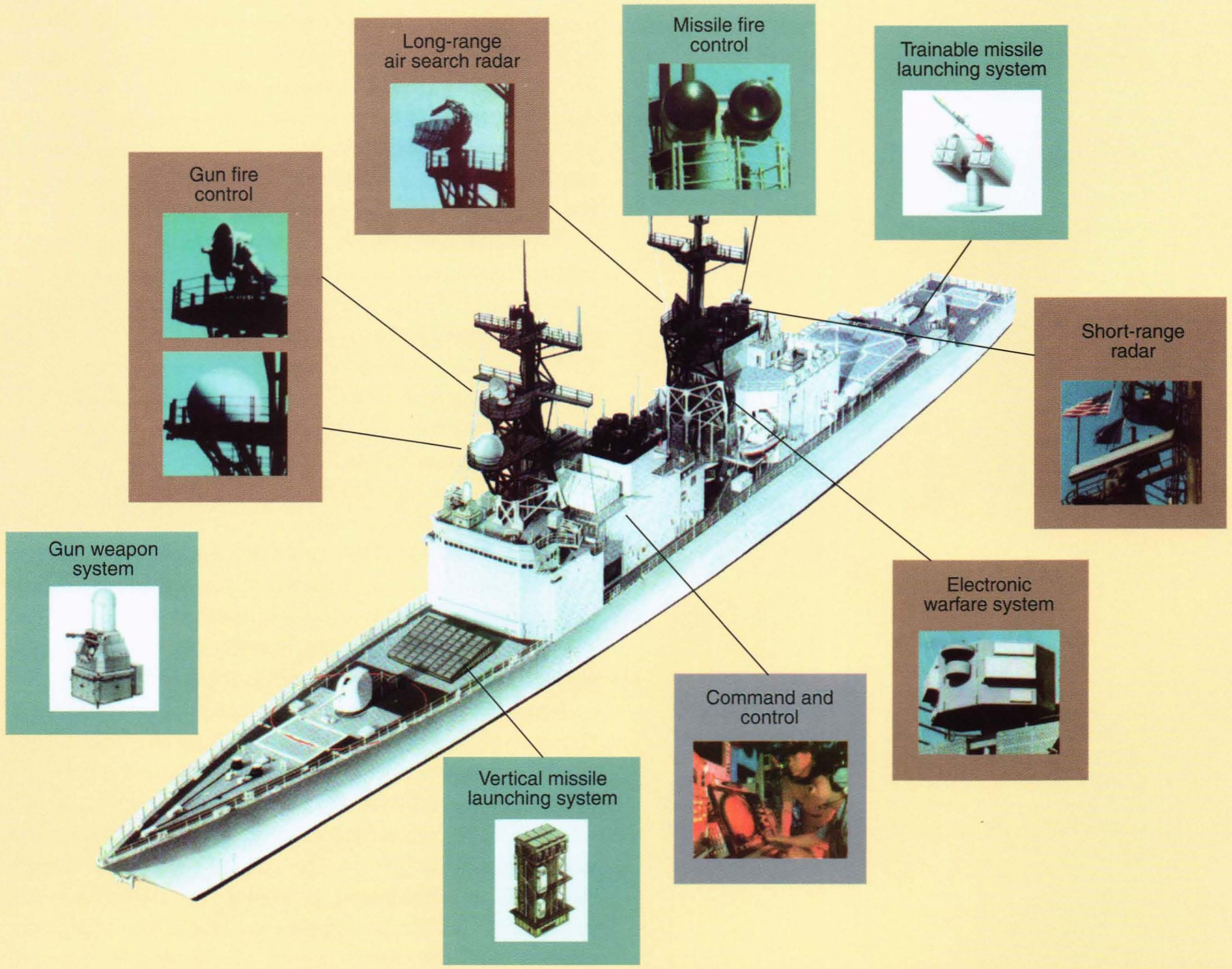

Figure 3. Typical elements of a ship's combat system. Characterization of combat systems must accurately describe the capabilities of ship detect (brown), control (blue), and engage (green) elements.

to carry out the sequence of steps that make up a target engagement, as shown in Fig. 4.

We can characterize the performance of target detection subsystems by determining sensor detection and firm track range under various conditions. Target engagement decisions may be based on target range, radial velocity, and intended direction. The performance of various sensor types (e.g., radar, infrared, electro-optical, electronic support measures), operating individually or collectively to fuse data, can be estimated based on target irradiance, emission characteristics, and radar cross section.

The performance of a control subsystem is often represented by its reaction time or the delay required to make decisions, determine priorities, exercise doctrine, communicate with weapons, and operate other subsystems. Other control processes such as kill assessment and target reengagement are also represented by time delays. General tactics such as salvo policies and firing doctrine are defined in terms of their use for given threat situations. Control can also be modeled through assumptions made regarding the state of other subsystems. For example, assumed ship readiness (e.g., "peacetime cruise" versus "threat alert") can be critical in determining the ability of the ship to detect and effectively respond to an incoming threat.

Engagement subsystems consist of hardkill weapons, such as surface-to-air missiles (SAMs) and radar-supported guns, and softkill systems, such as active electronic countermeasures (ECM), decoys, and chaff (small metallic particles intentionally released into the atmosphere). Characterization of a SAM includes its minimum- and maximum-range kinematic envelope, time-of-flight as a function of range, target kill probability as a function of both intercept range and threat type, and illumination time for terminal homing before intercept. Other system characteristics that determine effectiveness are the number and coverage of illumination channels, number and type of launchers, launcher cycle time, and magazine size. Similar characteristics must be

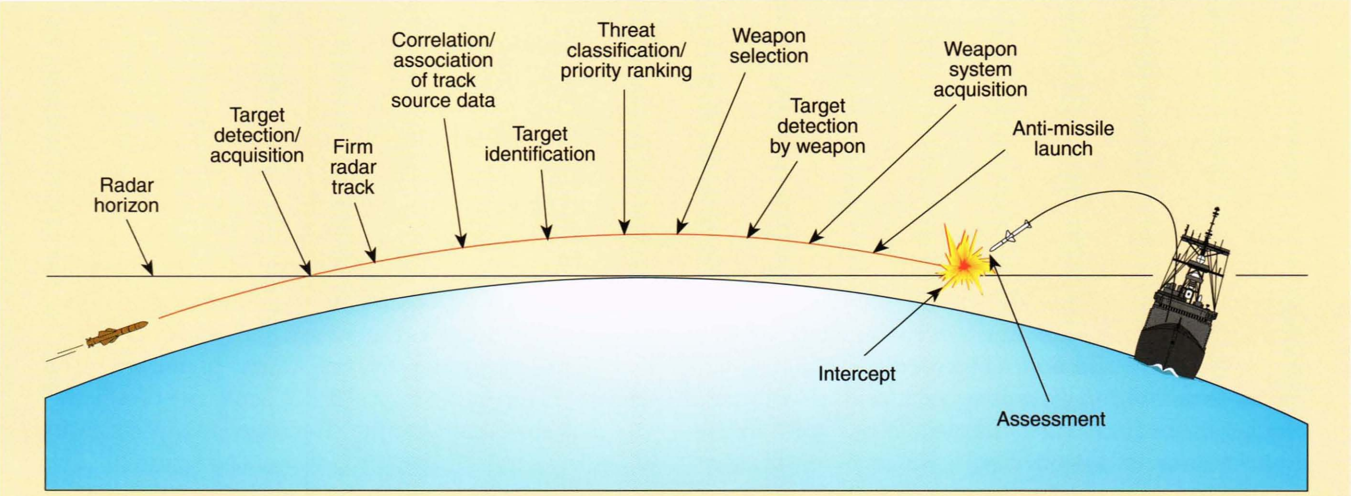

Figure 4. The detect-to-engage sequence may begin with long-range detection of threats where long-range sensors or battle group assets are employed to detect high-flying threats. Alternatively, for low-flying anti-ship cruise missiles, horizon limitations may impose a very short time line on defensive systems.

specified for gun weapon systems. Active ECM, decoys, and chaff are quantified in terms of their effectiveness and time required for deployment.

CHARACTERIZATION OF SCENARIOS

The specification of scenarios, including environmental parameters, is a critical step in the analytical process. Analysis is usually done to investigate a hypothesis or reveal a system's performance limits. A hypothesis may contain some preliminary set of expectations about system performance that is to be proven or refuted. A stressing scenario may be used to reveal operational limits or isolate areas in which a system should be improved. A more benign scenario may be used to study performance tradeoffs or act as a baseline against which to compare more severe cases. Care must be taken when specifying a scenario to ensure that it satisfies the purpose of the analysis.

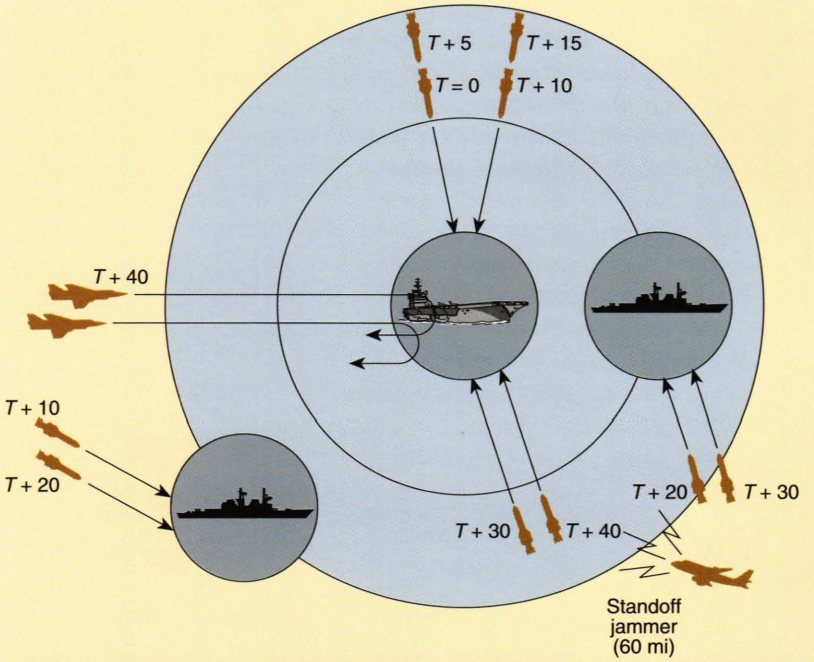

Figure 5. Scenarios are specified to reflect expected environments and raid densities. Arrival rates and formations that stress the automated systems and man–machine interfaces allow the analyst to study particular cases where special tactical procedures may optimize the ship's combat system response to the threat. The scenario specification would also include weather conditions, sea state, and radar propagation conditions. (T = time in seconds.)

Characteristics of a scenario to be defined include threat types, threat performance, raid description (number of threats and time separation), and the attack geometry (Fig. 5). Threat performance parameters include speed, altitude, and radar cross section. Attack geometries specify target heading, altitude profile, and maneuvers. A scenario is also characterized by the locations and types of friendly forces, both surface and air, that support the ship's AAW operations.

Environmental effects represent a major factor in combat system performance and, as such, receive significant attention in modeling and analysis efforts.

Shipboard AAW environments include both open-ocean and near-land locations where prevailing topography becomes a factor. The environmental effects considered in most simulation and modeling efforts are atmospheric propagation, electromagnetic interference conditions, sea-surface conditions, and land clutter.

The existence of air-sea and air-land boundaries creates several effects that must be considered. Multipath effects are caused when energy travels from its source to its destination along two paths, a direct path and a reflected path. As shown in Fig. 6, the direct and reflected signals add both constructively and destructively, depending on their phase relationships. Destructive interference is evidenced by nulls or "fades" in the signal power at various target ranges. Constructive interference is evidenced by peaks in signal power at other ranges. The location of the nulls and peaks depends on the height of the source and receiving antenna and on the signal's frequency. The reflected signal can bounce off either the ground or the sea surface. A smooth sea surface produces a pronounced multipath effect because very little of the reflected signal's energy is scattered in other directions. One effect related to multipath is the image of a target reflected from the sea surface as shown in Fig. 7. This effect is prevalent in smooth sea conditions and can confuse sensors and weapon systems.

The Earth's atmosphere causes several energy propagation effects. Representation of refraction, or the bending of rays in the Earth's atmosphere as shown in Fig. 8, can be simplified by using an "effective Earth radius" model in which rays are traced along straight lines and the Earth's radius is adjusted to support accurate distance computations. This approach greatly simplifies the geometry used in modeling the performance of sensors and target illuminators. The simplest form of refraction is that exhibited by a standard atmosphere. A decrease in the atmospheric index of refraction with increasing altitude causes a phenomenon known as superrefraction. An extreme case of superrefraction known as "ducting" traps the energy within its boundaries in the same way a waveguide would. The effect of ducting is to bend signals beyond the normal horizon (within a duct) and extend the range of sensors at low altitudes. This phenomenon can be helpful when the intent is to see objects beyond the horizon. However, ducting can also introduce large, unwanted signals from long range (e.g., large land masses, large ships), which corrupt or mask smaller signals from objects at shorter ranges. Ducts can occur at the Earth's surface or can be elevated above the surface as shown in Fig. 8. An increase in the atmospheric index of refraction with altitude at a greater rate than observed in a standard atmosphere causes subrefraction. Although less likely to occur than other forms of refraction, subrefraction bends rays upward, away from the Earth's surface.[3]

The characteristics of the sea surface have two effects. First, waves can reflect energy in the form of backscatter and forward scatter. Energy reflected by waves in motion appears as moving targets to sensors and weapons and produces what is known as sea clutter. Sea clutter can severely degrade the performance of sensors and weapons that must operate close to the sea surface. Second, the structure of the waves and the way energy is reflected, scattered, and diffused affect multipath conditions. As the sea surface becomes rougher, characterized by larger waveheights, multipath effects decrease. The motion of the sea and the corresponding waveheights are categorized by a sea-state number defined between 0 (smooth sea) and 8 (storm condition sea). Sea state is related to the wind and local sea current conditions.[4]

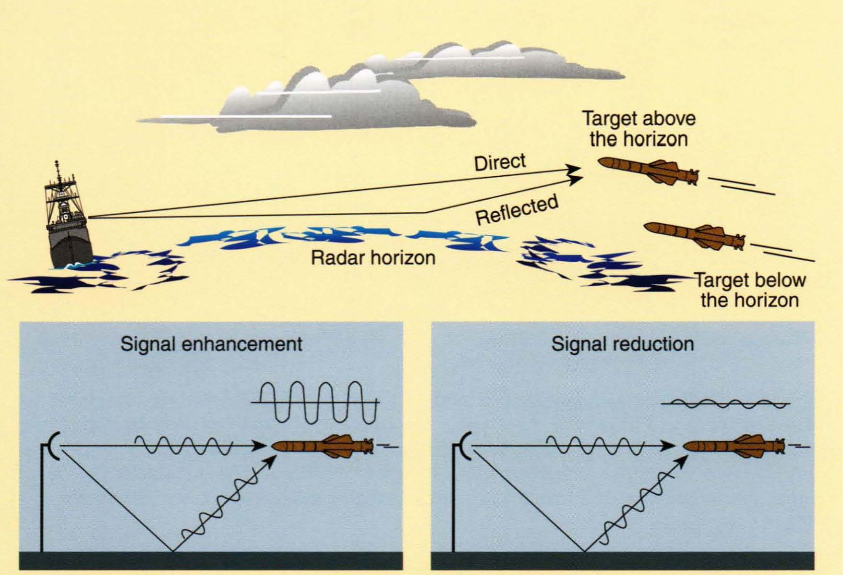

Figure 6. Multipath effects cause direct and reflected signals to be combined, resulting in either an increase or a decrease in signal strength. Signal enhancement or reduction depends on the path-length difference between the direct and reflected rays relative to the radar's wavelength. At low altitudes, the path-length difference becomes very small, and the direct and reflected signals cancel because of the 180° phase shift incurred by the reflected path at the sea surface. Environmental phenomena such as multipath effects must be accounted for in sensor modeling to provide an accurate representation of sensor performance.

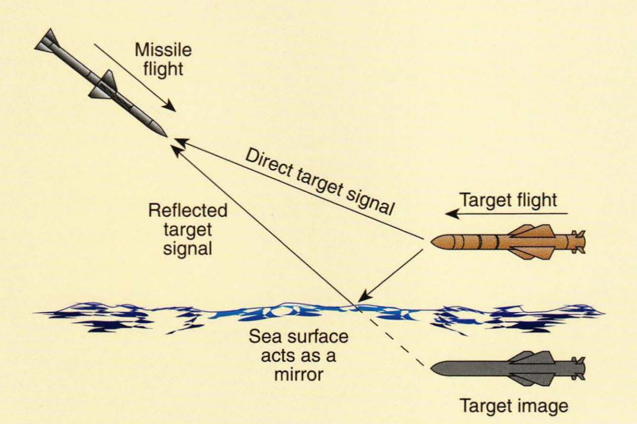

Figure 7. During low-altitude target intercepts the defensive missile is subject to the effects of the target image reflected from the sea surface. This can be problematic to the missile in resolving the true target from the target image, which may appear to be below the sea surface.

The characteristics of land masses and littoral where the land meets the sea significantly affect combat system performance. Any land mass reflects energy based on its physical and chemical composition. These energy returns are known as "land clutter." Although land clutter has no translational velocity, it cannot always be distinguished from moving targets because of its complex movements (e.g., wind-blown vegetation, man-made objects), large signal strength, and limitations of the receiver's signal processing techniques. Land clutter characteristics strongly depend on specific geographical features and time-varying conditions such as soil moisture and snow cover. They can also shadow other objects, especially air targets, and create complicated coverage problems for sensors and weapon systems. These complexities make it very difficult to model the effects of land clutter.[4]

Electromagnetic interference can be caused by both friendly and hostile systems. Friendly systems that operate nearby at the same general frequency can either deceive or desensitize radars, countermeasure systems, and missile seekers. Hostile interference, or ECM, exists in many forms. Each form attempts to deceive or desensitize the system being targeted. Chaff, which is used primarily as a defensive deceptive measure, can desensitize sensors and weapon systems. Decoys radiate energy signatures matching those of particular systems to draw attention away from other systems. They can be used to confuse sensors and weapon systems, both offensively or defensively.

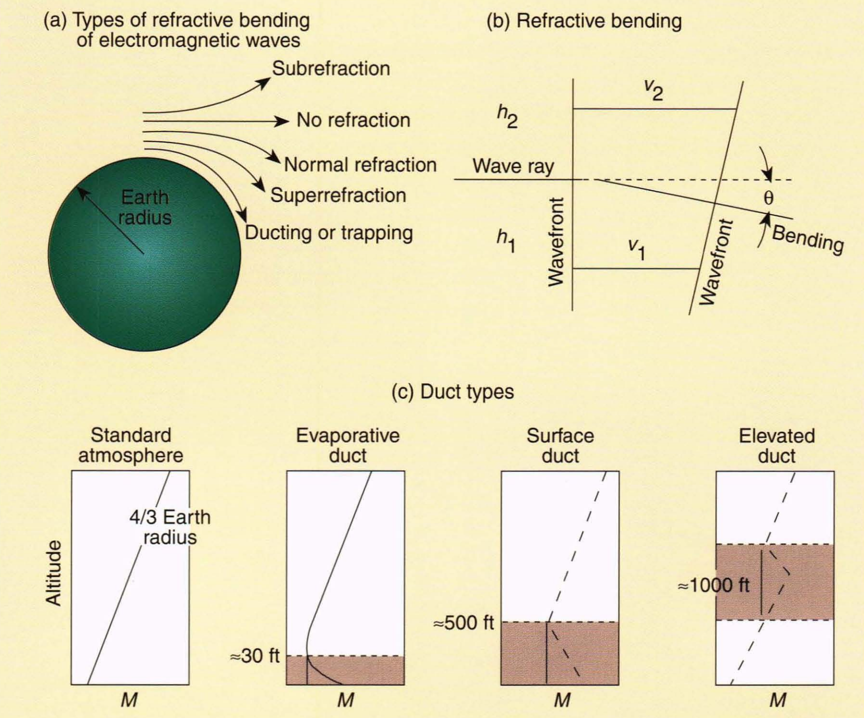

Figure 8. Energy propagation effects. (a) Depending on atmospheric conditions, many forms of refraction are possible that may direct electromagnetic waves along the Earth's surface or away from it. Ducting occurs when the upper air is exceptionally warm compared with the air at the surface, causing waves to travel along the Earth's surface around the horizon. Ducting affects sensor performance unpredictably, enhancing or reducing detection ranges. (b) Refraction occurs when propagation conditions change with altitude. At the different heights *h*, electromagnetic energy travels at different speeds *v*, causing it to bend at an angle θ. (c) Refraction in the atmosphere is related to changes in temperature and humidity with altitude. Graphically, the atmosphere's index of refraction *M* can be plotted as a function of altitude to illustrate the conditions that lead to the different forms of refraction shown. In a standard atmosphere (no ducting), *M* increases linearly with altitude. When *M* decreases with altitude, a duct is formed.

MODELS AND SIMULATIONS AS ANALYTICAL TOOLS

A model of a combat system is meant to constitute as true a technical representation of the system as is valid for the study at hand. As used here, the term model refers to any representation of a function or process, be it mathematical, physical, or descriptive. The term simulation more specifically refers to a computer program that represents the operation of a function or process and produces comparable outputs to that function or process. Models and simulations can be simple and used to identify problems and trends. They can also be complex hardware/software facilities intended to directly support development and testing activities.[5] Results obtained from models and simulations should be compared, whenever possible, against the latest empirical data and test results for the system being modeled. This process is known as benchmarking. Models and simulations should be periodically updated to recognize equipment upgrades. As models mature along with the systems they represent, they can become powerful tools for the prediction of system performance. System performance trends and relationships among controllable system parameters established through modeling and simulation can be interpreted and then coupled with the experience of naval operations to develop operational policies and tactics.

Many models and simulations are constructed to serve a specialized purpose. Once their intended use is completed, they are often archived and seldom revisited. However, with the advent of computer networking, catalogues of models and simulations can be compiled and made widely available. Potential users can be informed of various special-purpose models, which, when interfaced, form a network capable of simulating a total combat system. The Fleet Systems Department at APL has incorporated a number of specific models into an overall Ship Combat Systems Effectiveness Models Network, shown in Fig. 9.

Simulations of integrated target detection and track acquisition are used to assess shipboard sensor performance in combat situations. The specific detection and track acquisition process used by the designated shipboard surveillance system is simulated to generate estimates of target detection and track acquisition performance. The results are provided in the form of probability distributions of target range under specified target scenario and operating environment conditions. Each simulation comprises several parts that characterize detection and tracking performance, scenario effects, and propagation behavior. These parts can be configured to represent a variety ofsystems and operating conditions. Since RF and/or infrared refractivity profiles are required inputs for propagation computations, a refraction model is available to generate those profiles from raw meteorological data. Usually, stored profiles corresponding to known environments (e.g., evaporative ducts of various strengths) are used. An RF propagation model provides RF propagation factor values over the target trajectory for computing radar detection probability. The propagation model is run off-line with a fine range increment, and the precomputed propagation factor values are stored for use with the sensor models. Individual sensor simulations provide probabilities of detection in either search or cued modes at each detection opportunity over the target trajectory. Using the detection probabilities from the individual sensor simulations as input, track-state probabilities can be iteratively computed over the target trajectory in a Markov chain representation of the applicable track acquisition/promotion logic.

Missile flyout simulations for a variety of missile systems have been developed to predict flight performance. The models are characterized by the number

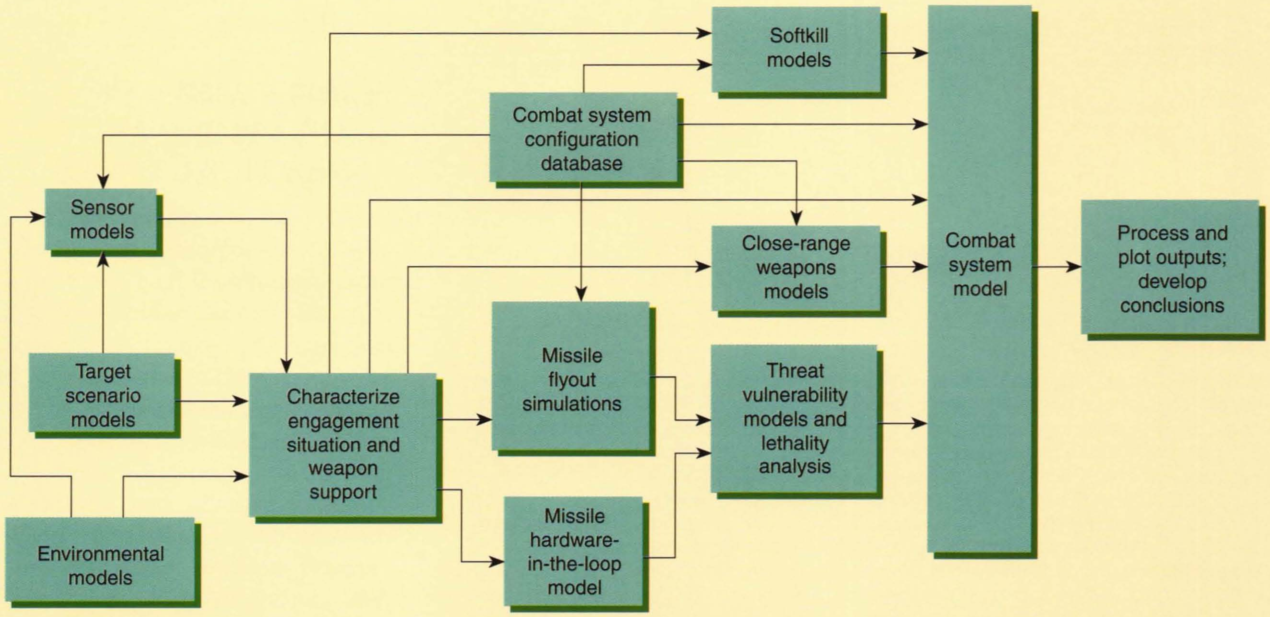

Figure 9. Modeling of a ship's combat system must address the pertinent elements of the system and may consist of several specialized models integrated together. A network of models, as illustrated, becomes a powerful tool for analyzing combat system operations.

of translational and rotational degrees of freedom (DOF). Three-DOF simulations represent the missile's translational motion only; 6-DOF simulations represent the missile's translational and rotational motion. A flyout simulation requires detailed definition of the missile's launch, guidance control, actuator systems, ship support system, target characteristics, and attack geometry. The flyout simulation dynamically computes kinematic parameters for both the target and missile throughout the engagement to determine how close the missile will get to the target at intercept, defined as the miss distance. Miss distance depends directly on the accuracy of the guidance system; seeker performance in the presence of multipath, sea image, and clutter; and the missile's ability to quickly respond with sufficient kinematics to exceed target movements at intercept. The missile's success also depends on where the intercept occurs in range relative to the missile's maximum effective range. Flyout simulations are run over many iterations to compute statistical results for such parameters as miss distance and time of flight as a function of intercept range. These results characterize missile performance against a given threat and are used in higher-level combat system simulations.

Hardware-in-the-loop (HIL) facilities can be used to measure in-flight missile performance parameters and to produce results similar in form to those generated by flyout models. These facilities combine real missile hardware with simulated functions to produce more detailed and accurate results. As shown in Fig. 10, a HIL facility can consist of an actual missile guidance section placed in an anechoic chamber to allow realistic signal propagation; the missile guidance section is connected to a computer, which provides the user interface and simulates other missile functions. Target signals are either propagated inside the chamber or directly fed into the missile receiver to allow for a variety of tests and measurements. The HIL facility is especially useful for studying a missile's response to multiple targets that are very difficult to represent with pure computer simulations. Such facilities have significantly reduced the gap between computer simulations and expensive operational tests.[6]

Threat vulnerability models are used to assess the susceptibility of specific threats to damage by defensive weapons. The models are constructed by identifying vulnerable components of the threat (e.g., guidance components, propulsion components, warhead), whose damage would cause destruction of the threat or prevent it from completing its intended mission. Results are based on actual test warhead firings against signature plates, simulated targets, or actual targets combined with miss distance predictions from missile flyout models or HIL facilities. The model provides the distribution of warhead material placed on the target, as represented in Fig. 11, and determines if it is expected to destroy or disable the target.

Close-range weapons models are used to determine combat system effectiveness for various sensor-guided gun systems based on firing rate, target range, and target vulnerability. These weapons represent additional layers of defense that complement missile systems and other primary weapons. Probability of kill for each weapon is computed as a function of intercept range to be used in the overall combat system model. Softkill models assess the contribution of ECM, decoys, and chaff to the ship's defense. The inclusion of these additional combat system elements in performance analyses contributes to a more complete representation of the system's capabilities.

Combat system models use as inputs the characteristics and performance of individual subsystems, and

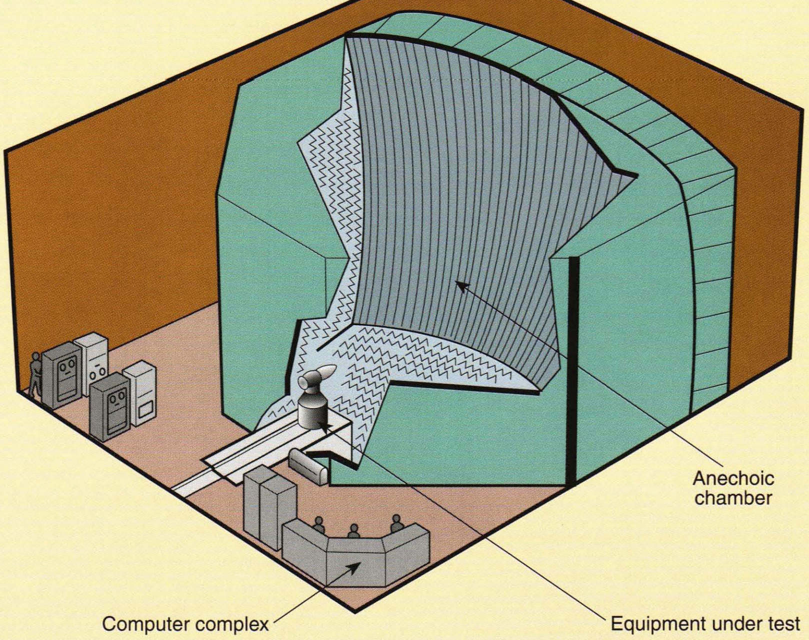

Figure 10. Hardware-in-the-loop facilities typically consist of an anechoic chamber wherein actual guidance and control components can be simulated and their responses measured, studied, and fed into computer and end-game simulations.

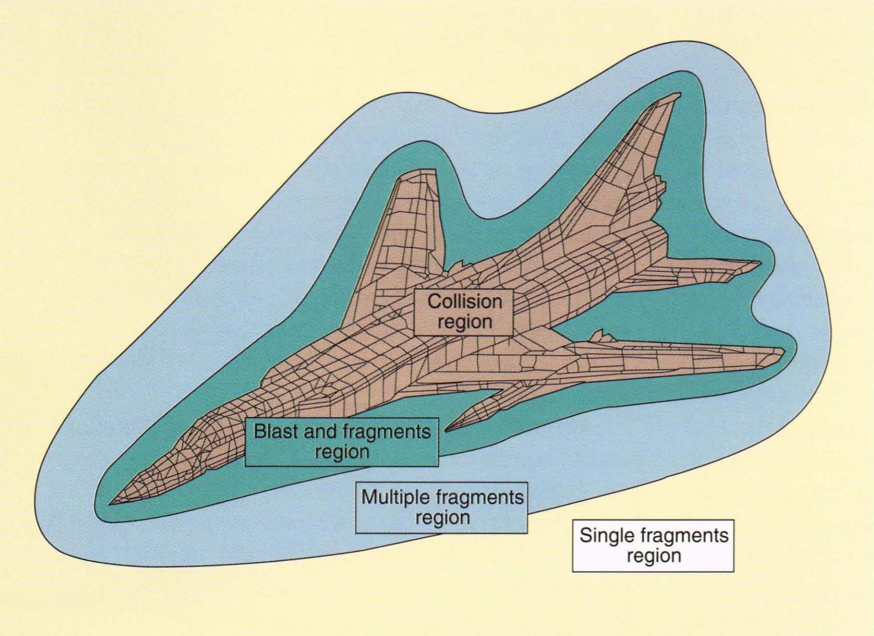

Figure 11. Threat vulnerability models are used to determine the effect of missile warhead (or gun shell) delivery. Based on missile flyout as determined by results from hardware-in-the-loop facilities, the missile-target proximity at intercept is used to compute missile probability of kill.

then determine a system's overall effectiveness in a defined scenario. These models exist in different forms (e.g., Monte Carlo simulation, mathematical spreadsheet), but all serve to indicate the impact of controllable parameters on performance, highlight a system's strengths and weaknesses, and estimate improvements in subsystem performance needed to achieve a desired level of system performance.[7]

Combat system models employ results from higher-fidelity models and simulations that characterize the detect, control, and engage subsystems, such as those described previously. First, targets are positioned according to the firm track range specified by the model(s) of the detection subsystem. Next, time lines are executed to include all specified reaction times and processing delays. Weapons are launched against the target for which possible intercept ranges are computed. The intercept ranges are then used to determine the probability of kill against the target. If the target survives the intercept, and if time permits, the target is reengaged. Models with multiple weapon layers can engage the target with different weapons. In simulating engagements, the combat system model includes system limitations such as illuminator tie-up (i.e., scheduling constraints on equipment use), kill assessment delay, weapon effectiveness envelopes, and equipment reliability factors. In general, a combat system model includes the major elements that determine the response of a ship or group of ships to a threat scenario.[8]

INTERPRETATION AND COMMUNICATION OF RESULTS

The final steps in the analytical process are to interpret the simulation results, draw a connection between what is modeled and what is real, communicate a complex conclusion understandably, and support the transition of the results into doctrine and tactics.

Computerized models and simulations simplify the analytical process, making otherwise laborious manual computations easy to perform. However, because simulations can produce vast quantities of information, the analysis of results can be more complex. A good method of visualizing the modeling results for both the analyst and the intended audience is therefore necessary. This is particularly true if multiple system measurables are being evaluated relative to one or more MOEs, as is often the case in comparative analyses of AAW systems.

The use of modeling and simulation introduces a level of abstraction from reality that must be understood if results are to be meaningful. All assumptions and limitations of the analysis, including the characterization of inputs and the representation of the systems within the simulation, must be known. Once results are obtained, we must apply what is known about assumptions and limitations so that we can interpret the results properly in the context of the real systems.

Recent advances in computer technology and the advent of commercially available plotting software have provided improved data display techniques that allow analysts to infer useful information from complex simulation results.[9] Engineers at APL have assembled several commercially available software tools on personal workstations that give analysts easy access to graphics displays and allow visual analysis of numerical data. Figure 12 depicts a type of plot known as a surface contour, which has been used to analyze and communicate results of AAW system simulations. It shows the effect of two critical measurables (the x and y axes) on an MOE (the z axis). Such plots are most appropriate for comparing system options and characteristics of different systems. A typical chart might plot an MOE (e.g., probability of escaping a significant hit, number of targets killed, number of missiles launched) as a function of system parameters (e.g., threat detection range, system reaction time, firing policy, target type, and raid density).

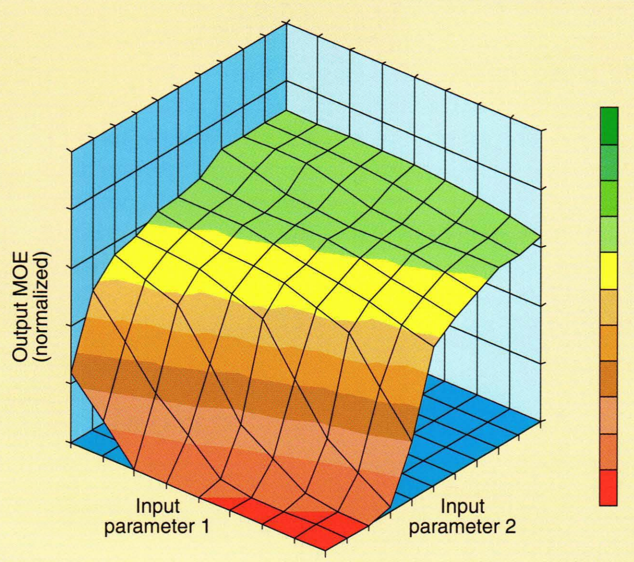

Figure 12. Abundant numerical data representing simulation results can be analyzed and communicated efficiently using graphical representations. Three-dimensional contour plots allow the effect of two independent input parameters on a third, dependent output to be seen. Colors on scale represent different values on vertical axis. (MOE = measure of effectiveness.)

Contour plots have been used to influence and shape decisions on a variety of Navy projects ranging from procurement of new systems and system upgrades to modifications in the way an existing system is used. In these instances, communication of the modeling results has been key. The plots have proven effective in conveying trends necessary to understanding the implications of an analysis; the alternative is reliance on raw data for the hundreds of cases these plots typically represent. Other graph types such as histographs, bar graphs, and x–y plots can also help to summarize, develop trends, or explore anomalies.

The effect of a third critical measurable on an MOE can be shown using animation of a contour plot (Fig. 13). Variation of the third measurable is represented over time in the animation. Animation allows us to visually analyze and communicate the effect of three system measurables on an MOE.

The significance of the numerical results produced by modeling and simulation is not always apparent. The analyst must carefully review the results and establish a correlation between input parameters, the scenario modeled, and their effect on MOEs. Beyond merely managing large quantities of information, graphical representation of numerical data enables the analyst to visualize data trends, making it possible to draw conclusions more easily and to see things that would otherwise have been undiscovered.

The plotting and animation techniques described are valuable tools for communicating the results of modeling and simulation. These results can affect tactics only if they can be communicated to those responsible for establishing tactics. Analysts and tacticians must work together to bring analytical findings to bear on real systems. Sifting through numerical data would encumber the process to the point that significant tactical improvements might be overlooked. Realistic graphical rendering of numerical simulation results allows complex issues to be understood where they might otherwise be obscure.

THE TACTICS FRAMEWORK

Tactical directives are designed to offer specific procedural instructions related to the use of ship combat systems or equipment or to promulgate approved doctrine for system operations. Tactics may be defined as actions and means of employing people and systems in combat situations to achieve a decisive advantage over an adversary. Doctrine refers to principles established and promulgated on the basis of past decisions and

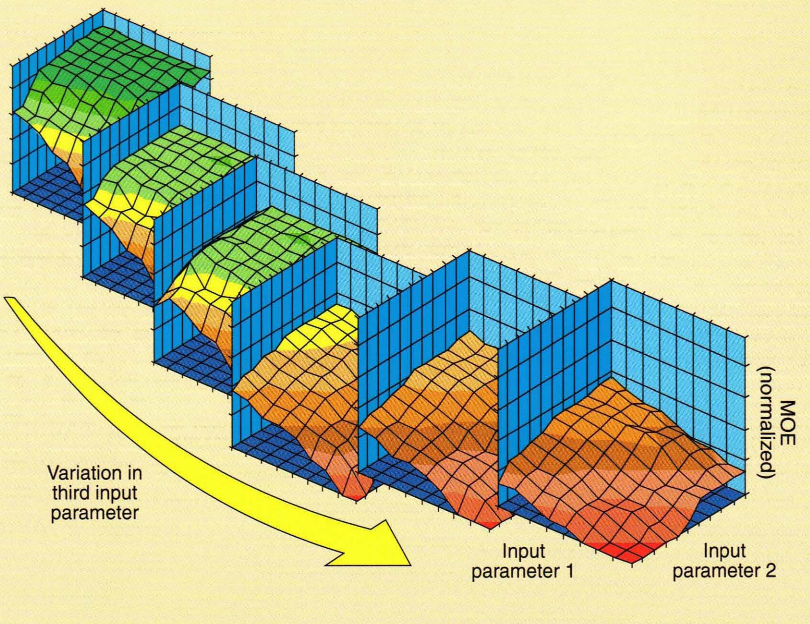

Figure 13. Animation of three-dimensional contour plots (e.g., Fig. 12) allows the effect of three independent input parameters on a fourth, dependent output to be seen. Colors represent different values on vertical axis. (MOE = measure of effectiveness.)

experiences. The Naval Warfare Publications series issues currently approved tactics, doctrine, procedures, and terminology. These publications incorporate the results of Fleet experience, provide information about the capabilities and limitations of equipment and systems, and include other pertinent data supplied by system commands, laboratories such as APL, and other Navy organizations.

In addition, the Navy has established a tactical development and evaluation program to provide a formal framework for the development of new or modified tactics and procedures. The preparation, approval, and distribution of tactical development information are the responsibilities of the Fleet commanders-in-chief and their designated subordinates such as the Surface Warfare Development Group. That group, working at the direction of the Naval Doctrine Command,[10] publishes findings in directives such as Tactical Memoranda (Tacmemos) and Tactical Notices (Tacnotes). Other NATO navies have similar groups and activities defined to offer tactical assistance or directives to their fleets.

Tactical Memoranda discuss and describe proposed tactics to elucidate the logic that supports the tactics. In addition, they provide analytical calculations, if any, that can be used to support the logic, so that another analyst can readily understand the methodology and appreciate the quality of the data used. Tactical Notices are promulgated after tactics are fully evaluated, tested, and approved as doctrine.

Tacmemos and Tacnotes provide the tactical commanding officer and various equipment operators with procedures to obtain maximum capability from their particular systems (Fig. 14). Tactical considerations for operations in a variety of situations and environments and against a spectrum of expected threats are included. When available, quantitative measures of system performance are also given for further guidance. Many early documents of this kind were based chiefly on the experience and judgment of warfare officers and operators. Such assessments, however, fail to address all situations pertaining to stressing scenarios and threats not yet encountered through Fleet operations. These conditions must be represented in operational tactics based on simulation, modeling, and analysis efforts.

TRANSITION OF ANALYTICAL RESULTS TO TACTICAL DIRECTIVES AND DOCTRINE

Air battles conducted at long ranges or over large areas may be evaluated and defensive actions directed by the officer in tactical command, commensurate with the identified threat. However, to provide a quick-reaction capability against close-in or pop-up anti-ship cruise missiles, system functions and system decision-making logic must be preset. Optimum performance is achieved when the parameters of these preset functions are derived from mission and tactical goals and constraints. The purpose of ship's doctrine is twofold: (1) to provide the mechanism for command/operator specification of mission and tactical goals and constraint parameters and (2) to define the ship's detect, control, and engage sequence in response to those parameters.

Tactical doctrine includes procedures and guidance for setting equipment modes and specifying the degree of operator interaction desired (automatic, semiautomatic, or manual). Zones (e.g., controlled reaction, nonradiation, automatic reporting) and operations may be specified. These are coupled with specified actions within each zone, for example, process only hostile tracks, engage at maximum range, display identification, etc.

Tactical doctrine also includes the determination of how the combat system equipment is to be used in concert with rules of engagement and enemy order of battle, while dealing with special problems of environment (natural and man-made). Doctrine must also take into account, and have the flexibility to respond to, the preferences of the tactical commanding officer and the operators acting at his direction.

On the basis of analytical results, operators may determine how to employ hardkill weapons, obtain a threshold (acceptable) kill probability, use missiles and guns in layered defense strategies to weaken and defeat a raid, and space successive missile salvos to ensure that

Figure 14. The officer in tactical command must direct AAW defense with a complex of sensors, control systems, and weapons. Tactical guidance for the use of the combat suite allows the officer to make timely responses and judgments based on the best assessment and advice formulated by tactical planners who have studied similar situations.

subsequent encounters are not made in the same illumination nulls.

These analytical conclusions also allow the formulation of strategies for softkill weapon employment (e.g., laying and reseeding chaff; using active, emitting decoys; activating onboard jamming devices). In addition, the coordination of hardkill and softkill assets can be specified for the best effect in defeating an attacker. The intent is to employ assets that can achieve an acceptable level of defense against each target, while not overengaging any threat such that assets are exhausted and follow-on targets cannot be engaged.

The analyst and tactician must remember that many operational constraints may affect or even negate clearly defined tactics. For example, ship maneuvers, while carrying out mission-specific actions, may be constrained by safe navigation or battle station keeping; employment of deceptive or seductive countermeasures may be curtailed because of nearby friendly units; and proximity of neutral shipping or air corridors may dictate cautionary use of sensors and weapons.

Analytical results obtained through modeling and simulation are used by naval tacticians as one of several inputs for developing the tactical instructions to Fleet units. The Naval Warfare Publications series is the first source of guidance for these tactical instructions. Rules of engagement also must be considered in formulating the instructions. Experience of the Fleet in actual operational situations, test and training scenarios, and wargame exercises also provides input (Fig. 15). There are obviously feedback processes whereby results of at-sea testing may indicate changes to the draft Tacmemos, which in turn may result in updating the models and simulations themselves.

CONCLUSIONS

Models and simulations are useful adjuncts to shipboard testing and experience in formulating guidance for the use of combat system elements in tactical situations. Analyses based on models and simulations provide helpful insights for decision making and, in certain situations, suggest specific tactics. Tactics must then be proven in simulated operations. As tactics are validated, they may be developed further into automated processes in the combat system computers.

When validated by at-sea testing, the results of analyses can be helpful in establishing policy for employment of combat system elements. Guidance for using specific combat system assets (sensors and weapons) under specific conditions of readiness can ensure optimal use of the combat system suite to meet a tactical threat.

Modeling and simulation efforts devoted to developing tactics also often result in exposing vulnerabilities of the Fleet to attack, despite the best employment of assets. Such results help identify needed system upgrades, new hardware/software developments, or availability/reliability improvements. They can also suggest investment strategies to obtain the needed capabilities.

The Laboratory has been involved in modeling and simulation efforts focused on the optimum use of Fleet systems (U.S. and NATO) in operational situations. Our studies have been driven mainly by the new emphasis on littoral environments coupled with the stressing supersonic, maneuvering, sea-skimming threat prevalent around the world. As funding becomes more limited, simulations will probably play an even greater role in establishing tactics. Trends expected to contribute to the escalated use of models include the rising costs of exercises and tests to evaluate systems, increasing complexity of hardware and software, and availability of more powerful computers and modeling facilities. In turn, simulations must be kept current and reflect the added complexity of computer-based combat systems. For modeling to fulfill its increasing role in tactics development, there must be more focus on these efforts along with Navy priority and resource commitments.

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Figure 15. The process to develop tactical guidance for the Fleet includes the distillation of information from several sources including combat system modeling; tactical guidance is proposed in Tacmemos, validated in at-sea testing, and promulgated in the form of Tacnotes and other directives to the Fleet.

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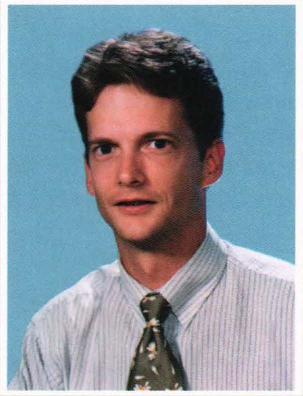
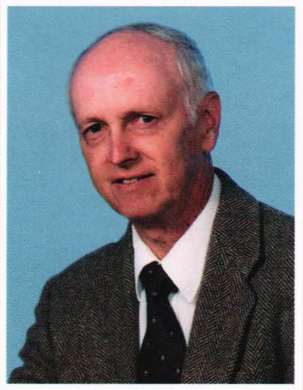
THE AUTHORS

SCOTT A. HYER received a B.S. degree in electrical engineering in 1981 from Rutgers University, an M.S. degree in electrical engineering in 1986 from The Johns Hopkins University, and an M.S. degree in technical management and systems engineering in 1993 from The Johns Hopkins University. Before joining APL in 1992, he was employed by the Westinghouse Electronic Systems Group for 11 years as a radar system engineer. His experiences included modeling, performance assessment, and design of radar systems. Mr. Hyer is now a senior engineer for the Fleet Systems Department involved in the analysis, development, and improvement of surface ship combat systems. He recently led an analysis effort to determine the impact of missile salvo policy on combat system effectiveness.



JERALD J. JOHNSTON is a senior physicist in the Fleet Systems Department's Anti-Air Warfare Systems Engineering Group, specializing in shipboard local AAW weapon systems. He received a B.S. in physics from the State University of New York at Binghamton in 1986 and an M.S. in electrical engineering from The Johns Hopkins University in 1991. Since joining APL in 1986, Mr. Johnston has conducted system integration and performance assessment analyses and design tasks relating to Fleet AAW systems. He has formed and led integration analysis groups involving representatives from academic research laboratories and industry, both domestic and international. His recent analysis of the combat system-level effectiveness of various AAW missiles when deployed with NATO ship variants has received significant international attention.



CHARLES L. ROE is a project manager in the Surface Combat Systems Program Office. He received a B.S. in computer science from The University of Maryland in 1984 and an M.S. in technical management from The Johns Hopkins University in 1988. Employed at APL since 1957, Mr. Roe has been involved in self-defense programs for the Fleet, and he has worked with the Surface Warfare Development Group and Naval Sea Systems Command Program Offices to develop Tacmemos for several ship classes. He has been particularly active in combat system analyses and integration efforts to attain improvements in self-defense for the Fleet.