

Systems-of-Systems Engineering in Air and Missile Defense

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This article explores the principles of systems-of-systems engineering and the application of these principles to air and missile defense. By examining structured approaches to designing complex systems-of-systems through specific applications, this article explains the need for clear requirements definition, assessment of existing capabilities and requirements gaps, thorough exploration of the concept space, allocation of requirements to the various elements, and evaluation of expected and demonstrated elemental and end-to-end performance. Simulation at the appropriate level of fidelity, driven by the questions to be answered and by the maturity of the design or concept, is necessarily an integral part of this disciplined approach. These principles of systems-of-systems engineering are illustrated through various specific examples: (i) building a common track picture capability across multiple units and sensors in the Joint Track Management architecture; (ii) end-to-end performance prediction and assessment for Aegis Ballistic Missile Defense; and (iii) development of investment strategies in way-ahead studies for future systems-of-systems capabilities.

INTRODUCTION

In the late 1950s, APL identified three major threats to the fleet for the next decade: surprise attacks by low-altitude missiles, confusion by raids of supersonic and high-altitude missiles, and confusion by electronic countermeasures.¹ In response, as part of the Typhon program in the early 1960s, APL developed a prototype phased-array radar for surveillance and fire control that could detect and track multiple targets and provide

guidance updates to several missiles in flight simultaneously, effectively integrating the radar, the missiles, and the weapons-control computer into a single system. Although Typhon was never fielded, many of the concepts developed in that effort formed the foundation for the far more capable Aegis system, which was developed in the 1960s and 1970s. APL played a key role in Aegis, including developing the advanced multifunction array

radar (AMFAR, later known as AN/SPY-1) and providing considerable insight into how to integrate the different elements into a single cohesive system.

In the 1980s and 1990s, APL developed the Cooperative Engagement Capability (CEC) with Navy sponsorship to counter a specific threat set. The perceived urgency and rapid prototyping precluded timely collaborative efforts with the developers of pathfinder “host” systems and tactical data links. APL also developed an extensive wrap-around simulation test environment to test the operation of the individual cooperative engagement processes interacting and to play back real data collected from sensors, combat systems, and cooperative engagement processors to analyze systems-of-systems behavior.

From 1987 through 1991, APL led an international team from six countries in performing critical experiments and developing concepts for a next-generation naval combat system. This North Atlantic Treaty Organization (NATO) anti-air warfare (AAW) system is made up of advanced solid-state phased-array radars integrated with ship defense weapons in an open-architecture, local-area-network infrastructure. While the solid-state radars were being developed independently, the U.S. team, led by APL, extended the critical experiment to a highly successful at-sea demonstration in 1993 and then through approval for service use and rapid deployment of this new Ship Self-Defense System (SSDS) in 1997–1999. These systems were deployed initially on large-deck amphibious ships and carriers because the NATO AAW program was ultimately cancelled. Significantly, after many years of development, dual-band, solid-state phased-array radars are being integrated with the SSDS in the USS *Gerald R. Ford* (CVN 78) class and follow-on combat systems, thus completing the six-nation NATO AAW vision. A second-generation SSDS system developed in the early to mid-2000s emphasized close integration of CEC with shared message infrastructures and development tools as well as specific allocation of composite track and custom weapon support functionality between the systems. This powerful architecture provides the basis for advanced cooperation and coordination between SSDS aircraft carriers and large-deck amphibious classes and Aegis cruiser and destroyer classes.

APL has a long tradition of supporting the U.S. Navy in bringing together systems-of-systems to solve air and missile defense problems that are beyond the capabilities of any single system. Through these and other efforts, APL has developed significant expertise in integrating systems-of-systems, as exemplified by a number of current programs.

Engineering complex systems requires a phased application of disciplined processes and systems engineering tools such as those shown in the APL systems engineering spiral or “loop,” discussed by Seymour and O’Driscoll in this issue. Systems-of-systems engineering

involves the same principles and disciplines as systems engineering, but it considers the behavior of a set of systems in the aggregate as a single system rather than only looking at each of the component systems individually. Systems-of-systems engineering is very powerful in terms of exploiting synergies between systems and in providing capabilities that no standalone system could achieve. This article provides three examples of complex systems-of-systems engineering that highlight different systems engineering methods used to develop and evolve current and future air and missile defense capabilities and systems.

The Joint Track Management (JTM) architecture example describes the systems engineering effort to develop a standard JTM architecture and common track manager capabilities that can be used across DoD air defense systems. This standard architecture presents a number of significant engineering challenges because the legacy systems were developed independently and have unique system architectures.

The end-to-end performance prediction and assessment for the Aegis Ballistic Missile Defense (BMD) example delineates a rigorous process for weapon system testing, mission planning, preflight performance prediction, and posttest mission analysis through the use of sophisticated modeling and simulation (M&S) tools. The challenge is to independently predict the performance of the Aegis BMD weapon system with enough fidelity to ensure success before the execution of extensive, complex system tests and also to assess test results afterward.

The way-ahead studies example describes an analytically based process that is intended to support sponsor acquisition decisions by clearly articulating the current and projected capability gaps and overlaps. The challenge is determining how to assess the capabilities of multiple weapon systems to counter expected threats in accepted tactical situations and then to determine the relative contribution of proposed system improvements in filling noted gaps. This information is intended to inform decision makers as they make difficult and complex acquisition decisions.

Although the specific systems-of-systems engineering disciplines highlighted in each example are different, all embody the principles of defining clear requirements, assessing existing capabilities and requirements gaps, exploring the concept space to define possible solutions, allocating requirements to elements of the solution, predicting performance of both system elements and the overall system-of-systems, designing and building solutions, and evaluating the resulting systems to determine how well the requirements are collectively satisfied. Woven through all these examples is the use of sophisticated M&S tools that allow the engineers and scientists to predict system performance, which is necessary to refine requirements, preview concepts, conduct trades, and test complex systems when live,

end-to-end testing is impossible (because systems have not yet been built) or impractical (because of the cost or difficulty of bringing all the systems together and using them in a realistic scenario).

JTM ARCHITECTURE

The Navy currently relies on a variety of combat systems to provide capability to its surface ships. The Advanced Combat Direction System, the SSDS, and the Aegis Combat System are presently on deployed ships, whereas new combat systems have been developed for the DDG 1000 and the Littoral Combat Ship. Although these combat systems have some overlapping capabilities, they were developed independently, each with a unique set of requirements and system architecture, and often by different developers. As a result, it has been difficult to reuse or modify code developed for previous or parallel combat system efforts. In addition, past combat systems tended to define their architectures so that the components within the systems were tightly coupled. Such coupling also hinders the ability to reuse existing capabilities and limits the ability to make isolated changes without affecting many of the combat system's components.

In recent years, the Navy has expressed a growing interest in applying open-architecture (OA) principles, such as the use of nonproprietary hardware and commercial operating systems, to future combat system development. Existing surface combat systems have started applying those OA principles in their system development. SSDS was designed with OA principles in mind, and Aegis has started implementing OA principles in more recent baselines. Although the application of OA principles may provide benefits within each individual combat system, their unique architectures continue to limit the ability to realize significant benefit across combat systems. As a result, there has been a growing interest in developing a standard architecture and common capabilities that can be used for a variety of both Navy and joint platforms. The JTM architecture developed such an architecture for track management functions typically contained within a combat system.

The JTM architecture was developed by a Joint Architecture Working Group (JAWG) composed of representatives from various organizations supporting the Army, Navy, Air Force, Marines, Missile Defense Agency (MDA), and the Joint Single Integrated Air Picture System Engineering Organization, which later became the Single Integrated Air Picture Joint Program Office. Over many months, the JAWG and its related splinter groups met and developed products to define the JTM architecture. Two of the key products developed during this effort were *Joint Track Management Architecture Precepts* and *SV-4 Joint Track Management System Functional Description* (documents are available from

authors on request). APL was a member of the JAWG and various splinter groups, including the Architecture, Track Management, Combat Identification, and External Communications groups.

JTM Architecture Precepts

The Architecture splinter group developed the set of quality attributes and architecture precepts that achieve those quality attributes. The quality attributes are nonfunctional requirements that are often discussed in software and systems engineering communities as “-ilities.” Examples of the quality attributes defined in the precepts document are availability, extensibility, affordability, and reusability.

To achieve the quality attributes, a set of architecture precepts was developed. These architecture precepts define a set of design principles applied in developing the JTM architecture. These design principles incorporate experience and lessons learned from previous Navy combat system development efforts and include basic design principles that can be applied to any system architecture. Several of the precepts that are particularly important for addressing the complexity of systems-of-systems engineering are described below.

The Information Model/Object Model precept provides a key design construct for the JTM architecture. It states that all JTM components shall be defined based on an information model. This model defines all of the information within the system. Each component is defined in terms of the information it uniquely produces (i.e., makes available to the system). All components have access to all information produced in the system, but the producer does not know which other components consume its information.

The Componentization precept specifies that the functional architecture be defined in terms of components that produce and consume information, consistent with the Information Model/Object Model precept described above. The JTM documentation refers to several definitions of a component, including the following from Booch et al.²: “A component is a physical and replaceable part of a system that conforms to and provides the realization of a set of interfaces.” Components are the basic building blocks of the JTM architecture, and they are characterized by the functions they perform, the information they require, and the information they produce. The definition above can apply to components of varying size; an additional facet of this precept is that each component be cohesive within its own boundaries while loosely coupled with other components.

The concept of a layered design refers to defining the architecture such that different levels of functionality are separated, isolating each layer from knowledge of the lower layers. A common example of this concept is using a standard interface to a set of library functions to provide networking services. The applica-

tion has knowledge of the standard interface but does not know about the underlying implementation. This setup limits the dependencies between the layers. The underlying implementation can change as long as the standard interface does not change, and, therefore, the application will not require any modification. The precepts apply the concept of layered design at several levels within the architecture.

Under the Hierarchical Track Data Integration precept, the use of a hierarchical track data model provides a mechanism for preserving track data from various sources while allowing a higher-level track that can combine the source data in some fashion. The lower-level track sources are considered supporting sources, and the higher-level track is referred to as a global track. The global track attributes, such as kinematic state or identification, may be created by fusion of the lower-level track sources or by selecting from the available sources. Figure 1 is a sample track data model.

JTM Functional Description

The JTM architecture defines a track management capability for receiving track-related data inputs from various sources, integrating those data to form a global track picture, and disseminating selected data over a variety of networks to other JTM nodes. As discussed in the preceding section, the JTM architecture is defined by its information design construct and its functional components. Several JAWG splinter groups were created to

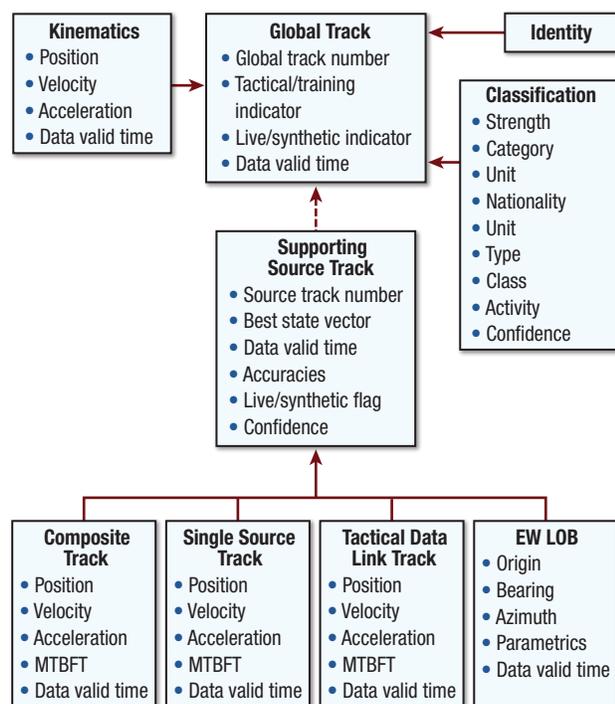


Figure 1. Example track data model. EW LOB, electronic warfare line of bearing; MTBFT, mean time between false tracks.

define the functional capabilities within the JTM architecture. These splinter groups brought together subject-matter experts from the government, laboratories, and industry to define the JTM architecture components in a given functional area. Each component was defined by a description of the functions provided by that component, as well as its inputs and outputs. The end result of this effort was a functional description of all the JTM components. Figure 2 is a subset of the JTM architecture illustrating both a tactical JTM and an operational JTM. The JTM architecture developed by the JAWG and described in this article is the tactical JTM.

Challenges

The task of defining a common architecture for a track management capability that can be used across a variety of joint units is challenging. It requires not only performing the necessary systems engineering across multiple systems but also doing so in a way that accounts for all the potential users who have different needs, systems, and operational constraints. As the splinter groups worked through defining their respective components, architectural decisions were driven by the need to satisfy all these requirements. Examples of these architectural decisions are described below.

The Navy currently relies on the CEC to provide a common air track picture on every CEC-equipped ship or aircraft in a battle group, allowing each ship or aircraft to see all targets detected by any other in a single combined, composite track picture. CEC computers that collect the data and form the composite track picture are connected to a network using the Data Distribution System, an RF communication system that provides connections and relays to get data from every platform to every unit in the network. The composite tracking process combines local measurements (from sensors on the same unit) with remote measurements (from other units) to associate all of the measurements made on a target into a track that estimates the target's position. The collection of tracks formed from all of the measurement data is the composite track picture. During definition of the JTM functions, the need was identified to allow JTM to accommodate multiple composite tracking capabilities. Such composite tracking algorithms should be formed with considerations for the error budgets in the host systems and take into account the presence of the tactical digital information links. One such need is the ability to run multiple composite tracking processes on a single JTM unit. For example, there might be different composite tracking processes for different types of sensors (e.g., radar sensors and electronic support sensors). The architecture meets this need by allowing the instantiation of multiple composite tracking components on a single unit, as illustrated in Fig. 2. The architecture also provides the capability to integrate the data from

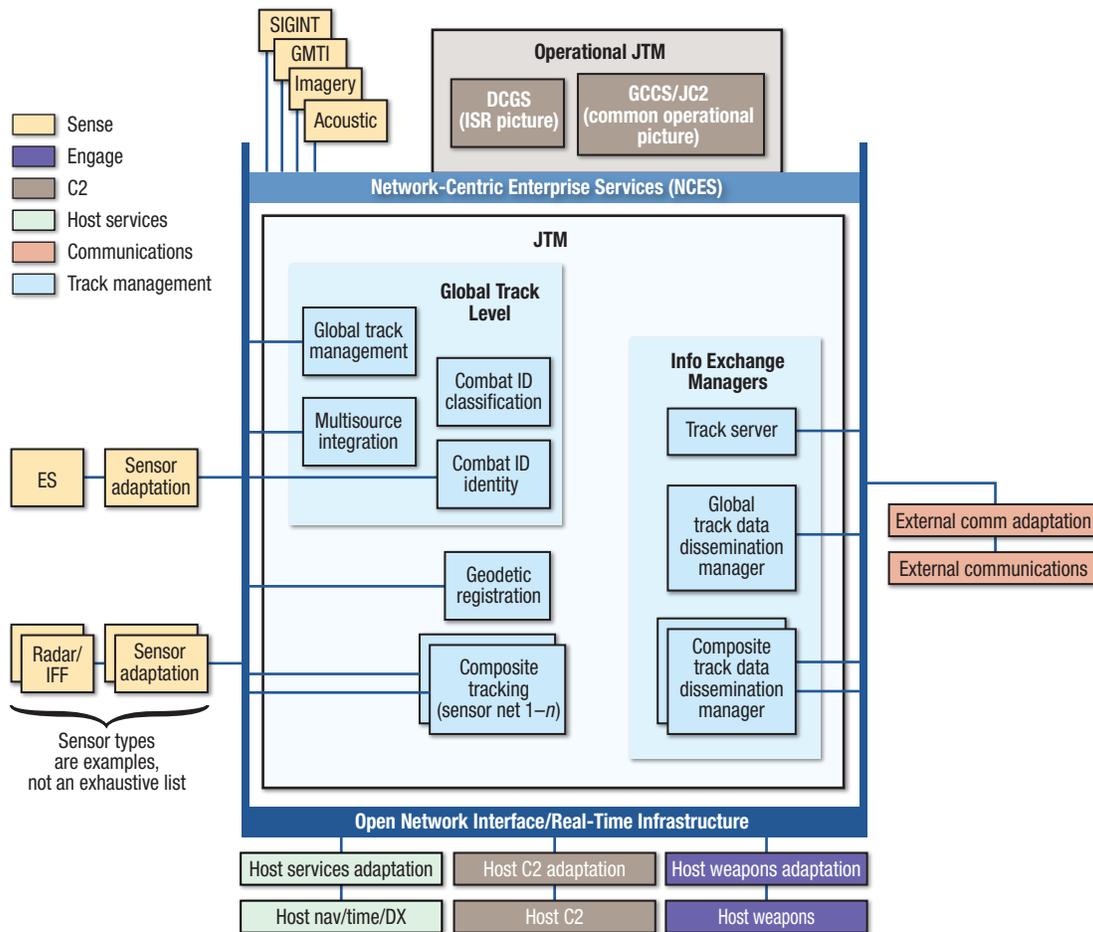


Figure 2. Subset of JTM architecture. C2, command and control; DCGS, Distributed Common Ground System; DX, data extraction; ES, electronic support; GCCS, global C2 system; GMTI, ground moving target indicator; IFF, identification of friend or foe; ISR, intelligence, surveillance, and reconnaissance; JC2, joint C2; SIGINT, signals intelligence.

multiple composite processes at the global track level by treating each as a unique supporting source. Integration at the global track level is essential to prevent dual tracks when two or more composite processes are detecting tracks in overlapping regions. A second need is the ability to allow for individual units or groups of units to select their own composite tracking solutions. The JTM architecture allows for multiple disparate composite networks operating simultaneously. The architecture provides for integration of tracks from disparate composite networks at the global track level.

The preceding paragraph describes the need to operate on multiple composite tracking networks that do not need to share sensor measurement data and therefore can be integrated at the global track level. There is also a need to operate on multiple disparate composite tracking networks while having a capability to share high-quality sensor measurement data between those networks. The JTM architecture achieves this need through the introduction of a bridging concept. Bridging provides a mechanism for maintaining the

relationships between tracks on each network, translating data formats and mapping track numbers as needed. In FY2011, a prototype capability to bridge the Army Integrated Air and Missile Defense Battle Command System composite network with the Navy CEC composite network was successfully demonstrated.

The use of a component architecture allows tailoring of the capabilities for each unit, allowing each unit to instantiate only those components that it needs. One example of this tailoring is implementation of a subset of components that operate only at the composite track level, leaving out components associated with creating and maintaining global tracks. However, these same units still need the capability to assess the identities of their composite tracks, which is vital to recognizing potential threats. Units that instantiate the global track-related components must perform the identity functions at the global track level. To satisfy both requirements, the Combat Identification (ID) components were defined to allow for instantiation at either the composite or global track level.

The Hierarchical Track Data Model assumes that data can be shared across the networks at both the composite and global track levels. As networks become larger, it is clear that bandwidth limitations will prevent all data from being shared, requiring algorithms for determining which data should be shared in a constrained environment. The JTM architecture addresses this challenge through the definition of the Global Data Dissemination Manager and the Composite Data Dissemination Manager components. Each of these components has responsibility for determining which data should be transmitted for their respective track levels.

Current Status

The previous sections introduced the JTM architecture precepts and functional descriptions. More recently, the Program Executive Office Integrated Warfare Systems (PEO IWS) has adopted a product-line approach for combat system software acquisition that defines a common software architecture for Navy surface units and the strategy for building and maintaining the components of that software architecture. The product-line architecture shares precepts similar to those defined for the JTM architecture, and the track management portion of the product-line architecture is very nearly the same as the JTM, having evolved from that architecture. However, the product-line architecture is broader than the JTM architecture, encompassing combat system capabilities beyond track management. The product-line architecture will be used to guide development of the common, reusable software components that will be maintained in a Common Asset Library. The government will control the Common Asset Library and the component-level architecture specified by the data model, the functional allocations, and the interface definitions. This architecture will serve as the basis for combat system development for future Navy surface ships. The initial baseline version of the product-line architecture is described in an architecture description document developed by PEO IWS.

Summary of Systems-of-Systems Engineering in the JTM Architecture

As illustrated by the various combat systems in use on Navy surface platforms, combat system capability can be implemented in multiple ways. The JAWG efforts to define the JTM architecture illustrate the complexity of defining a common capability across the services, given the varying systems and requirements of their respective ships. As both Navy and joint efforts move forward, it is important to recognize the complexity inherent in defining common capabilities and the need to thoroughly understand the requirements and constraints of all potential users so that the capability can be developed in

such a way that the requirements and constraints are satisfied. Efforts such as the JTM architecture definition can be achieved only through extensive cooperation among all affected organizations. The need for cooperation goes well beyond the initial description to ensure common understanding of all aspects of the architecture, correct implementation of all needed functionality, and rigorous testing of the systems being developed, both alone and in concert with other systems. Although the engineering challenges in developing common architectures are significant, an even greater challenge is the realization of products based on these architectures. Given the infeasibility of continually developing new combat systems from scratch, it is necessary to adopt an evolutionary approach to the development of common capabilities that is coordinated with existing combat system development efforts and that minimizes the impact to the schedules and budgets of those combat systems.

END-TO-END PERFORMANCE PREDICTION AND ASSESSMENT FOR AEGIS BMD

The MDA, along with the Navy, has developed the Aegis BMD system to counter short- and medium-range ballistic missile threats. The Aegis BMD system was built on the existing Aegis Combat System, which has been the combat system baseline for Navy cruisers and destroyers for many years. The Aegis BMD system incorporates the SM-3 for engagement of ballistic missile threats outside the atmosphere. The Aegis BMD system has been in development since the mid-1990s, has gone through an early demonstration phase, and is now in the production and deployment phase with the Aegis BMD 3.6.0.1 system with the SM-3 Block IA. One of the key parts of the early Aegis BMD development was a series of flight test demonstrations. As the Aegis BMD 3.6.0.1 system was readied for certification and deployment, flight testing was a key part of the systems engineering process.

Aegis BMD has long had a rigorous planning and execution process for flight testing. APL has been a key part of the government/laboratory team that performs mission planning, preflight performance prediction, and posttest mission analysis. The following sections describe the process for planning and executing Aegis BMD flight tests.

Modeling and Simulation

Strong M&S tools are an essential ingredient for the success of any modern development program. Aegis BMD is somewhat unique in that not only do the prime contractors develop and maintain simulation tools, but the Aegis BMD program also invests in APL to develop and maintain separate, independent simulation tools. This is critical to APL's role as

the designated Technical Direction Agent for Aegis BMD. Figure 3 shows the collection of Aegis BMD models and simulations. It includes all-digital models as well as hardware-in-the-loop (HWIL) tools. Figure 3 shows models from the contractors (Lockheed Martin and Raytheon) and models from APL, Naval Surface Warfare Center Dahlgren Division (NSWC/DD), and Massachusetts Institute of Technology Lincoln Laboratory. These models are developed in parallel with the tactical weapon system; therefore, early in the systems engineering process, engagement-level tools are available to perform initial requirements definition and early performance assessments. At this point in the process, the early flight test series is developed, and the results of performance assessments provide the framework for flight test development. The Aegis BMD program also has a rigorous verification, validation, and accreditation process for the models and simulations. As the system is designed, developed, and tested, the models and simulations are also being developed and evolved to capture the system design. The verification, validation,

and accreditation process lays out the requirements and criteria to be used to allow the simulations to eventually be accredited for a particular use. In the case of an Aegis BMD flight test, comparison between contractor and APL models is used as a means to verify that the simulations are behaving as intended, and comparison with ground test or previous flight test data is used to validate that the simulations are correct. This verification and validation evidence is provided to a simulation accreditation panel that decides whether the simulations are adequate to predict the performance of a flight test; if the simulations are adequate, the panel recommends to the Aegis BMD Program Director that the simulation be accredited.

Mission Development

The mission development portion of the testing process consists of two phases. The first is the refinement of near-term flight test plans, in which the systems engineers and the flight test engineers collaborate to

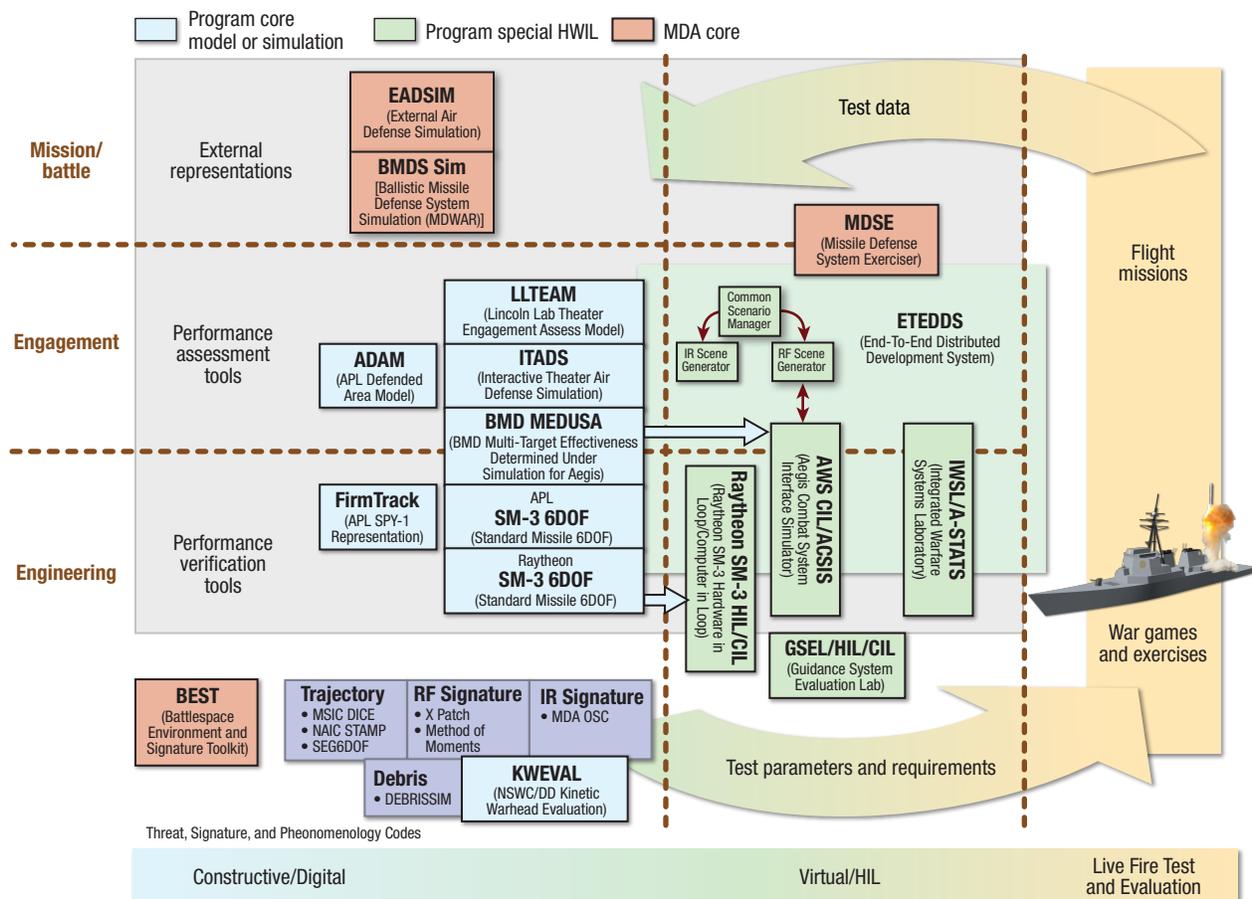


Figure 3. A snapshot of the Aegis BMD M&S “tool box” in 2008. This tool box continues to evolve. A-STATS, Aegis Simulation Test and Training System; DEBRISIM, Debris Simulation; MDWAR, Missile Defense Wargaming and Analysis Resource; MSIC DICE, Missile and Space Intelligence Center Digital Integrated Combat Evaluator; NAIC STAMP, National Air Intelligence Center Strategic and Theater Attack Modeling Process; OSC, Optical Code Signature; SEG6DOF, Systems Engineering Group 6 Degree of Freedom.

determine the top-level mission scenario and objectives. Within Aegis BMD, this process is performed by the Systems Engineering Planning and Test Execution Team. The systems engineers bring forward the requirements that need verification through testing as well as the critical functionality that needs to be verified through a live-fire test. High-level mission objectives are determined at this stage. For example, a high-level objective could be to demonstrate the intercept of a medium-range separating target. The test engineers bring forward test execution constraints, such as range-safety constraints, range availability, target availability, and test costs. The result of these discussions is a flight test schedule covering the next few years with top-level descriptions of the missions, including target types, numbers of participating ships, configurations, etc.

The next phase of the mission development process is the advanced planning phase. During this phase, Aegis BMD depends heavily on APL to refine the high-level plans and objectives discussed by the Systems Engineering Planning and Test Execution Team. APL typically uses the APL Defended Area Model (ADAM), a medium-fidelity model that simulates the major components of the kill chain and estimates overall system performance for various ship placements and threats, to help define more of the specifics of the test. ADAM generates the probability of single-shot engagement kill (P_{ssek}) over an operational area against a particular threat. This information is used to determine potential

test support positions for the Aegis BMD ship. It is also used to help refine test target parameters, such as target range, target apogee, and, for a separating target, separation velocity between the separating objects.

Once mission parameters are well defined, APL then uses its high-fidelity weapons system models [FirmTrack and SM-3 6 Degree of Freedom (6DOF)] to analyze the potential test scenario. Again, Aegis BMD typically relies on APL to perform the initial high-fidelity analysis to gain a better understanding of mission performance and any mission parameter sensitivities. The reliance on APL for completion of this task allows the prime contractors to focus on the design, development, and testing of the system. One example of the importance of such advance planning is the Aegis BMD FTM 04-1 (FM-8) mission. This was the first Aegis BMD mission against a medium-range separating target. Advanced APL analysis was used to determine performance sensitivities and, in turn, to determine selectable target parameters to maximize mission success. Figure 4 shows results from several steps in the mission development process.

Premission Analysis

Once the mission development process is complete, about 6–9 months before a flight test, the premission analysis phase begins. The mission review process is defined in a program document that specifies all major reviews leading to a flight test. The Scenario

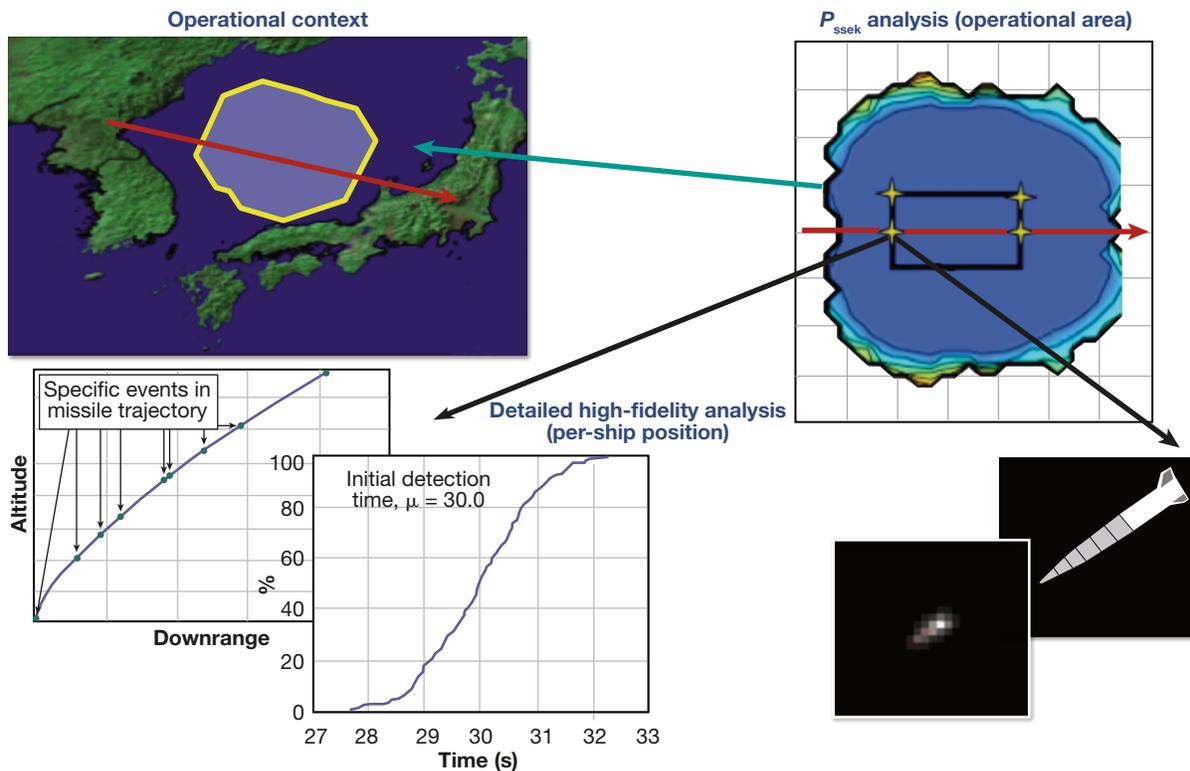


Figure 4. Aegis BMD mission development process results.

Certification and the Mission Control Panel (MCP) are the two reviews for which detailed performance predictions are required.

Scenario Certification is the first review in the process. As the name suggests, the Scenario Certification objective is to determine that the scenario as defined is sufficient to meet the stated mission objectives and that the mission can be executed safely within the capabilities of the system. The determination is based on the performance predictions generated by the high-fidelity weapon system models. At this point in the process, both Lockheed Martin and Raytheon are fully engaged in the preflight analysis. Figure 5 shows the analysis process used within Aegis BMD. The box at the top is the mission definition developed during the mission development phase, along with target-specific trajectories provided by the target contractor. The left side of Fig. 5 shows the Lockheed Martin and Raytheon analysis path. Lockheed Martin uses their high-fidelity Multi-target Effectiveness Determined Under Simulation for Aegis (MEDUSA) model to predict the performance of the Aegis Weapon System (SPY-1 radar, Command and Decision, and Weapon Control System). The output of MEDUSA is then fed into the Raytheon SM-3 6DOF simulation, which predicts the missile performance. The right side of Fig. 5 depicts the APL analysis path. This path is independent from the contractors and supplies a check and balance to the contractors' results. The APL FirmTrack model is a high-fidelity representation of the SPY-1 radar and Command and Decision. The output

from FirmTrack is fed into the APL SM-3 6DOF model, which includes not only detailed missile models but also a detailed representation of the Weapon Control System. The output of the 6DOF simulations is probability of hit, quantified as a miss distance between the target and the SM-3. That output is then fed into the NSW/DD Kinetic Warhead Evaluation (KWEVAL) model, which predicts SM-3 lethality. Given the 6DOF output, KWEVAL will determine the probability of a lethal intercept.

This information, along with several detailed metrics and measures of performance, is reviewed at the Scenario Certification. Both the contractors' and APL's analyses are shown. On the basis of this information, the panel decides whether the scenario will meet mission objectives and then "locks down" the scenario. The Scenario Certification occurs approximately 3–4 months before mission execution.

The second major review is the MCP. In addition to a review of the latest expected performance, the MCP also reviews the configuration under test to determine reliability, workmanship, and system integration. A successful MCP allows the process to continue to the mission execution phase. For the performance predictions, the identical analysis process described for the Scenario Certification is used for the MCP. However, additional analysis products are required, the most important of which is an update to the predictions based on the latest input data, more specifically, target data. This update includes the latest trajectory information, both RF and IR signature predictions, and any other aspect of the target that would result in a potential performance change.

Another aspect of the performance predictions that differs from those for the Scenario Certification is that HWIL testing will have been completed. The HWIL testing happens for the weapon system at the Combat Systems Engineering Development Site and for the SM-3 at the Raytheon Computer-in-the-Loop and HWIL facility. APL also performs HWIL testing of the SM-3 in the Guidance System Evaluation Laboratory. The HWIL testing provides an opportunity to execute the actual weapon system code and hardware with the flight mission scenario. The output of the HWIL testing is compared with the digital model predictions, providing critical validation data to support model accreditation. If an unexpected result happens in the HWIL testing, the result must be explained either as a test setup issue, a digital model deficiency, or an actual flaw in the weapon system design. This information is provided during the MCP to provide added confidence in the validity of performance predictions.

Key outputs from the updated performance predictions are the detailed target and missile trajectory data that feed the range-safety analysis. This information captures via Monte Carlo analysis the expected varia-

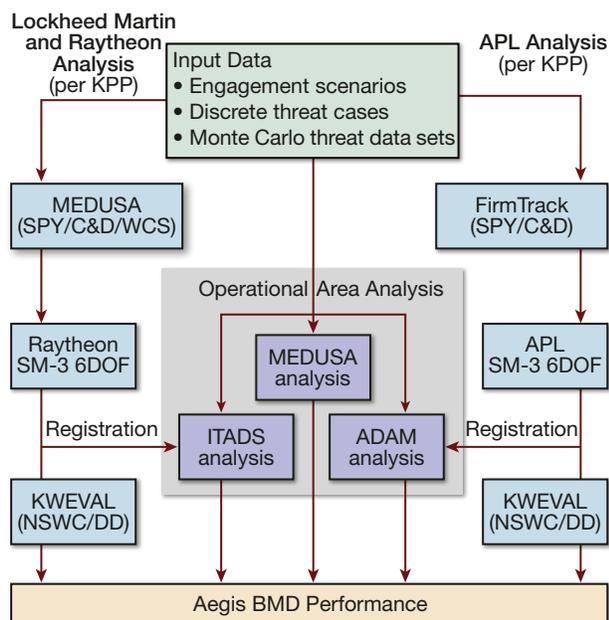


Figure 5. Community analysis process for Aegis BMD. C&D, command and decision; ITADS, Interactive Theater Air Defense Simulation; KPP, key performance parameter; WCS, weapon control system.

tion in target and missile fly-out. The range then uses this information as well as the Kinetic Impact Debris Distribution intercept debris model to determine the range-safety hazard patterns. The final hazard patterns are reviewed at the Mission Readiness Review (MRR) approximately 1 week before the test is executed.

Postmission Analysis and Event Reconstruction

After mission execution, the analysis team focuses on the postmission analysis and reconstruction. Three main data sources are used: target best estimate of trajectory (BET), Aegis Weapon System data tapes, and SM-3 third-stage and kinetic warhead telemetry. The target BET is developed with target Global Positioning System data as well as range radar tracking information. The data are merged to provide an estimate of the as-flown target position, velocity, and body attitude. The Aegis Weapon System data are collected onboard the firing ship and distributed to the analysis community. Both Lockheed Martin and APL have access to the raw data. The recorded data are extracted and processed and then compared to the preflight predictions. The analysts initially focus on the event timeline, i.e., when the SPY-1 radar detected, transitioned to track, and provided an engagement order, missile away time, etc. Likewise, both Raytheon and APL receive the raw SM-3 telemetry and process the data to compare with the preflight predictions. The analysis focuses on substantiating whether the primary mission objective was achieved.

The process for mission reconstruction can occur in several ways. One type of mission reconstruction, which is focused on the weapon system modeling, involves attempting to recreate the mission with the high-fidelity models. The process involves playing the target BET back through both FirmTrack and SM-3 6DOF and deterministically setting parameters based on the executed mission. For example, the exact ship position can be used rather than a random position within an operational area used for preflight predictions. Other parameters that may be set include ship heading and speed, wind speed and direction, rocket motor temperatures, etc. Of course, not every modeled parameter is measured during the flight test, but the data are rerun through the models to try to achieve a “mission match.”

Another type of mission reconstruction occurs with the auxiliary sensors. After the test, all auxiliary sensor data, including data collected from range radars, airborne optical sensors, and land-based optical sensors as well as weapon system and SM-3 data, are collected and compared. The objective is to reconstruct exact intercept conditions and describe the postintercept debris characteristics and intercept phenomenology. The result of this analysis is a 3-D visualization of the mission reconstruction and a detailed event timeline.

Feedback in the Systems Engineering Process

The final and perhaps most important step is incorporating the feedback of what was learned from the test into the systems engineering process. After a successful mission, the flight test data are used to verify system performance metrics and requirements and to validate the weapon system models. If the test mission is unsuccessful, the postmission analysis is used to carefully analyze what happened in order to determine what went wrong and why. In either case, lessons learned from the flight test are provided to the systems engineers so that issues leading to undesirable system behavior either can be corrected in the current baseline or noted for further consideration in a future baseline development. The observations are also provided to the operational fleet. Any observed issues or limitations revealed during a flight test are shared with the warfighters to help them better understand the system they are operating.

WAY-AHEAD STUDIES

A way-ahead study produces an analytically based investment strategy that clearly articulates to decision makers the current and projected capability gaps and overlaps to help focus acquisition decisions and guide future technology development efforts. APL's Air and Missile Defense Department and Business Area have conducted several of these studies for the Navy, to assist high-level sponsors who perceived a strong need for such a strategy when determining what Navy systems and associated improvements are required to defeat threats to Navy forces today and in the future. Fiscal constraints require that the Navy spend its acquisition dollars to obtain the best possible performance against the full range of current and anticipated threats.

Background and Motivation

Historically, major program managers within a single organization have pursued funding from their resource sponsor for developments within their product lines without fully considering solutions outside of their individual spheres of influence. These requests for funding often lacked sufficient analytical underpinning and, in some cases, relied more on contractor claims for particular systems' performance than on an integrated systems-of-systems engineering approach, which sometimes resulted in overlapping solutions to similar problems and did not succeed in maximizing the impact of acquisition funding.

In 2001–2002, at the direction of the Program Executive Office for Theater Surface Combatants (PEO TSC), APL compiled the first version of a way-ahead study focused on Theater Air and Missile Defense (TAMD). There was a need within PEO TSC to prioritize Program Objective Memorandum (POM) proposals for future

funding requests submitted by individual programs. The types of questions that needed to be answered at high levels within PEO TSC were, for example, whether to invest in a new radar or a new missile for a given ship class or whether some combination of the two would be the best option. Before the way-ahead process, high-level decision makers within PEO TSC had no effective method to make these decisions comprehensively. The TAMD Way-Ahead Study allowed the PEO TSC team to speak with one clear voice in terms of a coordinated POM submission that had investigated the trade space and resulted in a solid systems engineering solution.

APL, in its Technical Direction Agent role, participated in supporting the PEO TSC's (ultimately PEO IWS) initial effort to develop a way ahead for TAMD. This effort was also supported by other Navy warfare centers and laboratories, including the NSWC/DD, the Naval Air Warfare Center Weapons Division at China Lake, and the Naval Research Laboratory. The effort was funded and managed by PEO IWS but was also used by the Office of the Chief of Naval Operations (OPNAV) as an analytical basis for funding decisions.

The TAMD Way-Ahead Study included performance assessments of the deployed, planned program of record (those programs funded within the presidential budget) and potential future program elements, including sensors, C2 systems, and weapons. These assessments were made for current and evolving TAMD threats in both benign and more realistic operational environments (including jamming, land clutter, and various RF propagation conditions). Element-level capabilities and limitations were asserted via vignettes that showed either a carrier strike group or an expeditionary strike group under attack. The attacks focused primarily on anti-ship cruise missiles but also addressed, to a lesser extent, aircraft, land-attack cruise missiles, and ballistic missiles. Also included in the TAMD Way-Ahead Study was a series of charts listing stressing attributes (e.g., an anti-ship cruise missile or an operational environment), what

about the attribute causes the stress, what aspects of Navy combat systems are affected, and what systems and technologies are required to counter the stressing attribute. The TAMD Way-Ahead Study assessed most of the systems within the purview of PEO IWS.

The TAMD Way-Ahead Study continued for roughly 3 years. The plan had been for the TAMD Way-Ahead Study to continue to be updated on a regular basis to support the POM/program review process. There had been plans to update the vignettes to be consistent with the OPNAV-approved Major Combat Operations, to update threat characterizations as necessary to be consistent with current intelligence assessments, to add fidelity to the combat system modeling where appropriate, to account for potential system resource issues when simultaneously conducting multiwarfare area operations (e.g., AAW and BMD within the TAMD mission), and to include a health assessment (i.e., an assessment of the reliability, maintainability, and availability of the systems under consideration). However, driven by a focus on the program execution details during POM issue development, the acquisition program planning process later came to emphasize schedule and cost estimation more than technical assessment of the way ahead. Many of the capability improvement recommendations from the earlier way-ahead cycles are included in these business-focused planning products, but the process of periodic, technically based capability assessment and improvement evaluation has not continued as originally planned. To remain relevant, a rigorous systems-of-systems engineering approach to making informed acquisition decisions must include up-to-date technical assessments.

Process Methodology

An overall process for conducting way-ahead studies, shown in Fig. 6, was established and agreed to by PEO IWS, APL, and the pertinent Navy laboratories. The first step is to define the threat scenarios in which

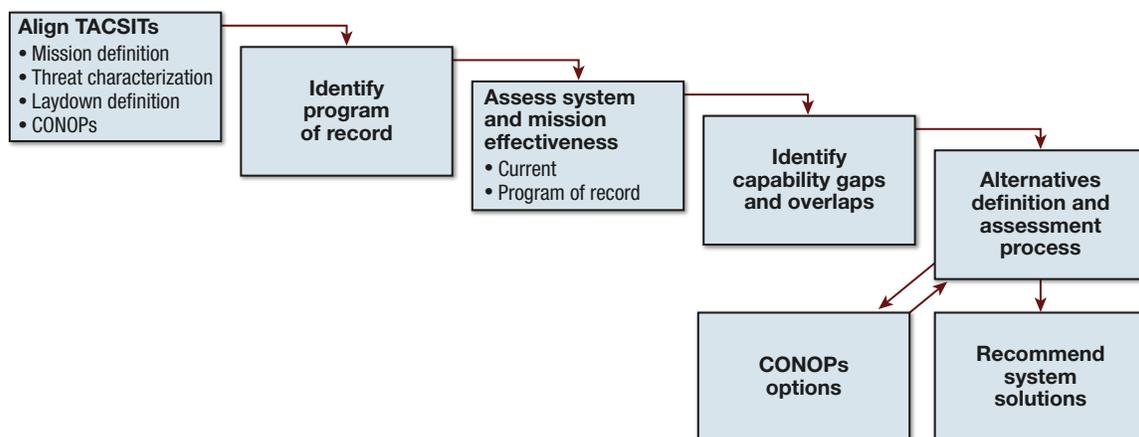


Figure 6. Way-ahead process. TACSITs, tactical situations.

Navy forces will operate. This includes determining the mission or missions of the forces, the threats they are expected to face, the dispositions of Blue (self/friend) and Red (foe) Forces, the environments in which they need to fight, and the Blue and Red Force concepts of operation (CONOPs). These are all critical inputs to the process. Buy-in throughout the community is essential in this area, so reaching consensus at the start is key to the successful development of an investment strategy and saves time and energy in the long run.

The next step is to identify current and program-of-record Blue Force ship configurations (i.e., what equipment do the ships have with which to fight?). This is not as straightforward a step as might be expected because there is often debate about which systems are funded, whether they are fully funded, and to what level their integration is funded.

The third step is to assess system and mission effectiveness. This assessment starts at the element (e.g., radar or weapon) level, is aggregated to the ship level, and is then further aggregated to the mission or strike group level. Many M&S tools are required to generate the various levels of performance data that collectively quantify effectiveness. Often the challenge is to evolve existing models or build new models at the appropriate level of fidelity to conduct the performance assess-

ments. Figure 7 shows the M&S process for conducting such assessments. Although better integration of these models can be an effective way to capture the dynamic interactions between systems, it can also pose huge challenges in finding the right balance between fidelity and responsiveness.

Once current and program-of-record performance assessments are completed, the performance gaps and overlaps are identified. If performance gaps are observed, candidate element, system, and system-of-systems solutions need to be developed or proposed to potentially alleviate the performance gaps. Often, M&S tools need to be modified to represent these proposed solutions at the element and mission levels. Another critical factor to be considered at this stage is changes to Navy CONOPs because it is possible that CONOPs changes rather than new or upgraded systems are needed.

The final step is to provide analytically based recommendations to the acquisition sponsors regarding what systems provide the best value to the Navy. By providing an integrated vision of an effective system-of-systems solution to counter the threats of greatest concern, individual sponsors can clearly understand the key performance drivers and consequently propose how their programs can most effectively contribute as part of the larger system-of-systems.

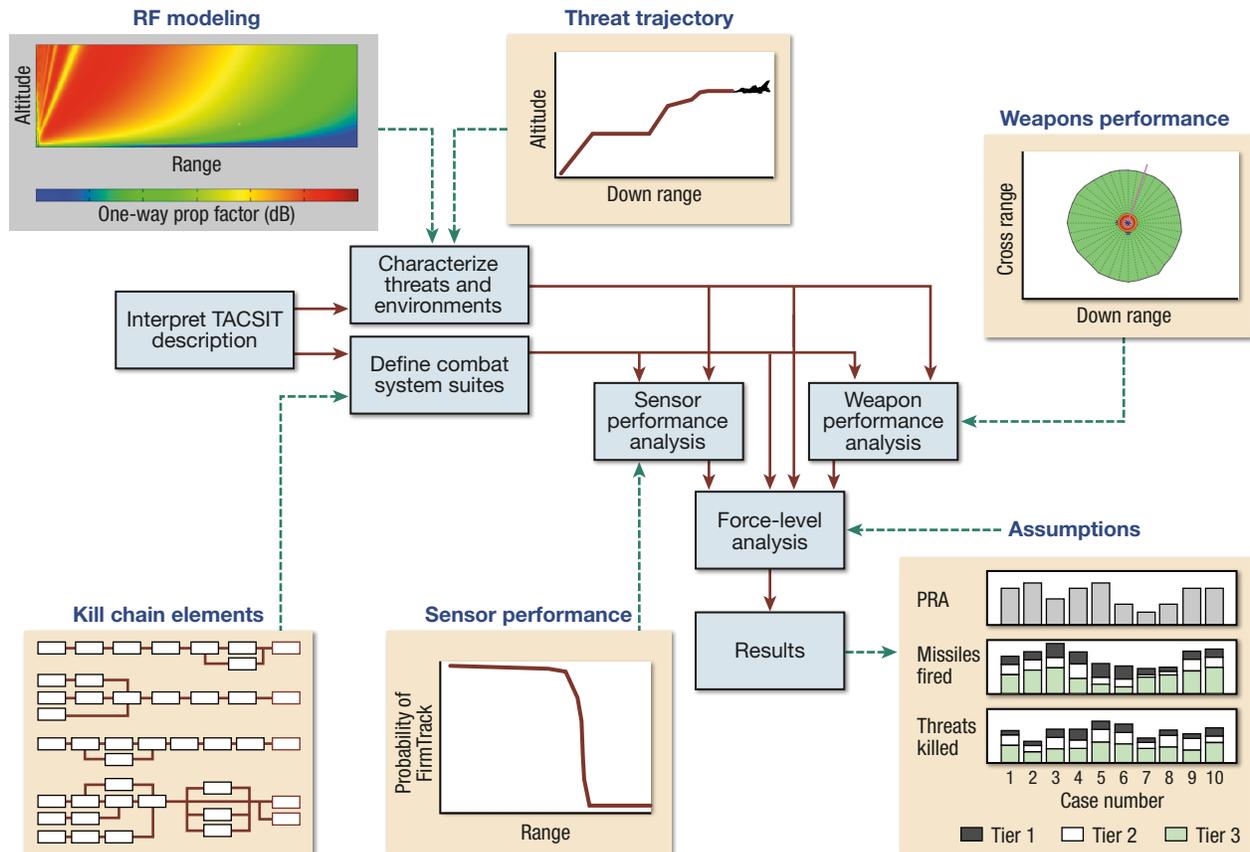


Figure 7. Way-ahead M&S process. PRA, probability of raid annihilation.

Lessons Learned

APL staff members supporting investment strategy efforts have learned some valuable lessons that should serve APL and other organizations well in conducting similar analyses in the future. Establishing and communicating an investment strategy development process is crucial to building collaboration and consensus among participating organizations and stakeholders. Incorporating suggestions and changes to this process as it is communicated will help create two-way communications and promote buy-in. An investment strategy that many organizations developed and promoted is a more powerful product than one supported by a single organization.

Investment strategy analyses and recommendations will be heavily scrutinized because they are designed to influence funding decisions. To withstand this scrutiny, it is crucial to include the highest-fidelity analyses possible and to clearly articulate any underlying caveats, limitations, and assumptions. It is also critical to remove any real or perceived bias in the results and conclusions of the analysis. Establishing the pedigree of the analysis inputs and M&S tools can help to eliminate

the perception of bias and enhance the credibility of the overall results.

In presenting an investment strategy, there is rarely time to discuss all the details of the underlying analyses. Carefully constructed illustrations and animation sequences have proven to be very helpful in quickly distilling a large body of information for an audience. The use of succinct yet powerful graphics that convey well-supported information has been very effective in capturing and keeping the audience's attention. However, it is also important to illustrate the depth of the underlying analysis results. This can be done by choosing an analysis-based assertion (e.g., a system capability versus a particular threat in a particular time frame) and drilling down to various levels of analysis results that substantiate this assertion. An AAW example could involve a high-level depiction of the scenario, followed by a graphic containing ship-level probability of raid annihilation statistics, followed by an engagement timeline showing probability of detection, reaction time, and weapon probability of kill for each intercept opportunity within the raid. Figure 8 shows some sample illustrations of results. In illustrating a weakness of the system-

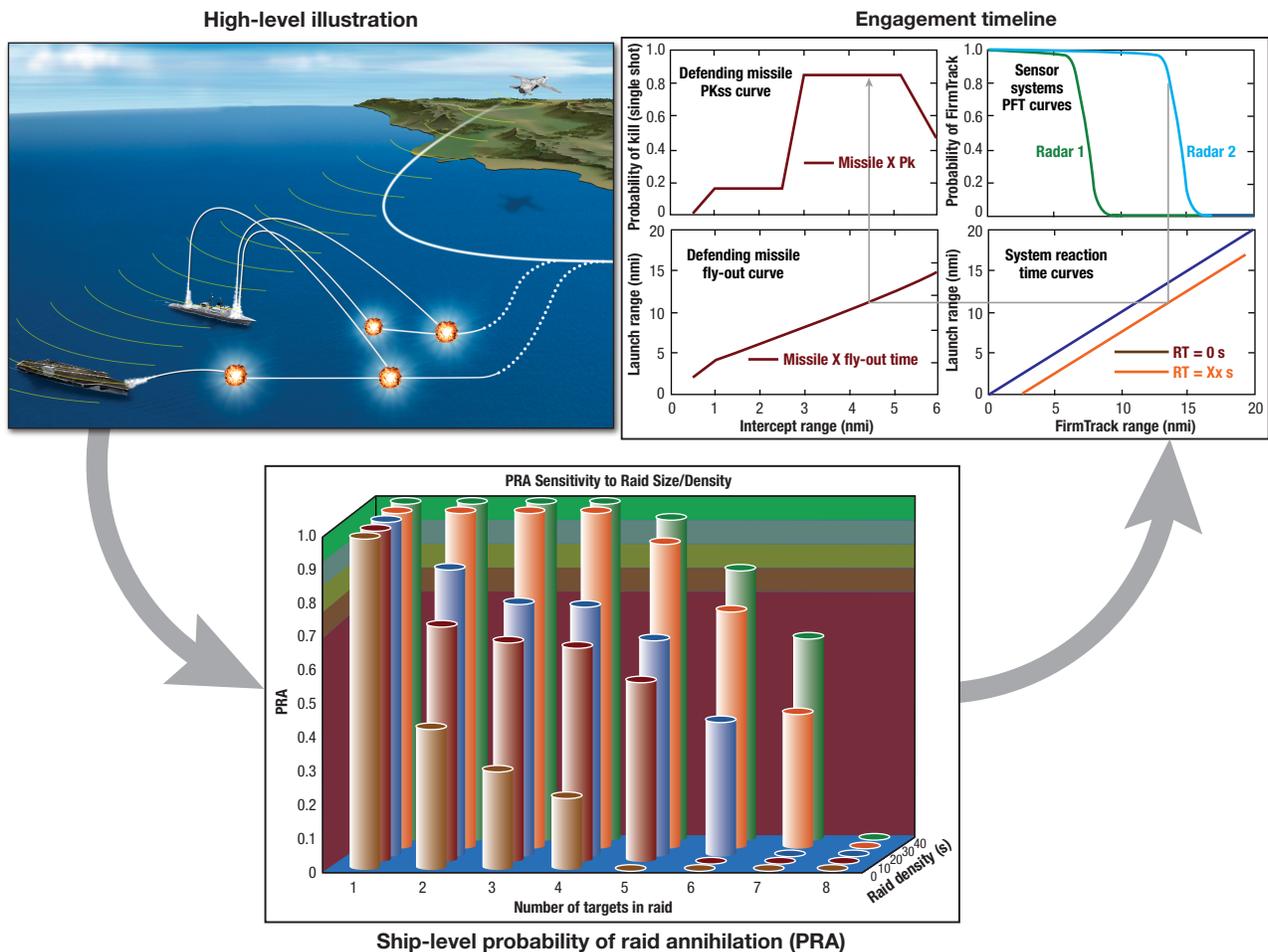


Figure 8. Sample illustration of way-ahead study results.

of-systems, it is often essential to drill down to these details to identify the weak link or links in the detect, control, and engage sequence. In presenting an investment strategy, any component can be challenged at any time, and therefore the presentation team would ideally consist of the appropriate subject-matter experts. This is not always possible, of course, so the presenter must be as familiar as possible with all of the analysis details and underlying assumptions.

Perhaps the most important lesson is that the sponsor needs to champion the investment strategy effort for it to provide the fullest potential impact. This championing should start with the highest-ranking member of the sponsor's organization. That person needs to emphasize that the effort is a top priority for the organization. This high-level championing will help ensure that all subordinates take the effort seriously and contribute accordingly.

Current Status of Way-Ahead Studies

Although there has not been much momentum behind systems-of-systems way-ahead studies in recent years, there has been some renewed interest from PEO IWS in analytically based investment strategy efforts. Over the past 2 years, APL, in close cooperation with other Navy laboratories, conducted an Integrated Layered Defense System study to provide the Navy with investment strategies and force structure recommendations to establish a defense-in-depth capability against advanced threats. The primary focus was on enhancements to existing Navy and MDA systems to provide a layered defensive capability in a timely manner. The previously defined way-ahead analytical process was leveraged for this study. The study was chartered by PEO IWS and Aegis BMD and included participation by OPNAV, the Office of Naval Research, the intelligence community, and various Navy laboratories. A series of technical interchange meetings was held to agree on methodology, share results and conclusions of the analysis, and come to consensus on the recommended investment strategy. Gaps in our defensive systems were identified, and concepts were proposed to improve performance. Improvement options were explored, and their relative benefits were captured through high-fidelity models and simulations of element- and force-level systems. The final Integrated Layered Defense System product delivered to the sponsors was a time-phased investment strategy that established an incremental approach to implementation and deployment of improvement options to facilitate building capability over time. The recommendations have been briefed at the highest levels of the DoD and will likely influence acquisition decisions for the next several years.

Investment strategies may be seen as a luxury, in that they do not directly impact the design or development of an individual system. However, such an instrument is essential in comprehensively communicating an organization's overall systems-of-systems capabilities and limi-

tations while simultaneously communicating its vision. APL continues to feel that there is tremendous value in this process, which can benefit both the sponsors and the participating organizations.

CHALLENGES FOR SYSTEMS-OF-SYSTEMS ENGINEERING

As illustrated by the three examples described in this article (JTM, Aegis BMD, and way-ahead studies), systems-of-systems engineering has inherent challenges beyond those faced by other systems engineering efforts. First, because multiple independent systems are integrated into a coherent set of cooperating systems, the technical complexities are often much greater than those for a set of subsystems designed from the beginning to work together. Agreements on interfaces, functional decomposition, and interpretation of shared data as well as common understanding of complex interactions and a shared vision of how the systems should work together as a system-of-systems become extremely important and are difficult to achieve. Second, because multiple programs with multiple program managers and multiple sponsors are involved, with no one necessarily in charge, some products normally produced by a single program (for example, Navy Training System plans, CONOPs, and technical inputs to tactical documentation) are more difficult to produce for the operators.

Simplification and concept generalization to reduce the complexity and interdependencies of the interactions wherever possible, as was described for JTM, can help to make tractable even very complex integrations of systems-of-systems. For Aegis BMD performance assessment and way-ahead studies, the interfaces and functional interactions are between simulations rather than between physical systems, but the same principles are often used to achieve well-integrated analyses with credible results.

Third, systems-of-systems typically comprise some combination of legacy systems, upgrades to legacy systems, and systems in various stages of development. Considering this in the context of the systems engineering spiral, deployed legacy systems, systems under development, and systems still in the phases of needs definition or concept exploration may all be key elements of the overall system-of-systems. Because the requirements developers and individual system designers for the system-of-systems do not have the luxury of starting with a clean slate, compromises are needed to make the most of the available or partially developed capabilities while avoiding expensive redesign as much as possible. Backward compatibility with fielded systems and minimizing changes in partially developed systems must be balanced with the need to incorporate more powerful, joint capabilities. Going forward, such concerns yield an argu-

ment for developing systems that can interact in generic ways with a variety of other systems and that employ flexible architectures that are amenable to future not-yet-understood changes so that the system-of-systems can evolve and improve its capabilities as new systems become available for integration. For JTM, Aegis BMD performance assessment, and the way-ahead studies, integrating either the systems themselves or their predicted performance is a key challenge that requires element designers of systems at different levels of maturity and at different points on the systems engineering spiral to share a common interpretation of both interface definitions and functional interactions, as described for the first challenge.

Fourth, and much more difficult to successfully address than the technical issues, are what we will call the programmatic or cultural issues. Because systems-of-systems typically involve a number of systems developed by different acquisition sponsors, program offices, and industry partners, each with its own responsibilities and priorities, it can be very difficult to persuade them all to design their systems to achieve the best possible system-of-systems. One difficult question for those working on the system-of-systems aspects of the problem, as opposed to the development of an individual system, is “who is in charge?” Although system-of-systems efforts typically have a high-level sponsor who is interested in integration and performance of the system-of-systems, that sponsor may not have direct authority over all the individual acquisition programs needed to implement the system-of-systems concept. It is therefore essential for the individual system sponsors to clearly see the value of the proposed concept and to be strongly supportive of putting the necessary attention and resources into achieving a viable system-of-systems. Without strong leadership and a strong sense within the community that the system-of-systems is the way to go, the tendency is for individual programs to focus more heavily on their own requirements because that is the responsibility they have been given. Whether the problem is development of a new system-of-systems, development of a new capability that enables systems-of-systems such as the JTM architecture, a detailed end-to-end performance analysis, or a way-ahead study, without strong support from the high-level sponsor and full participation from pertinent organizations, systems-of-systems efforts are very difficult to bring to fruition. Whether from the sponsor community, the DoD laboratories, the contractor community, or an independent organization such as APL, a persuasive advocate that can clearly articulate and sometimes even demonstrate the potential benefits of the system-of-systems can be extremely useful in moving such concepts forward.

Regardless of how development of the system-of-systems is structured, the effort needs to have a requirements document at the system-of-systems level to allow flow down into the component system requirements

documents. It is essential that requirements be unambiguous, that they reflect the needs of all the stakeholders, that they define both interfaces and functional interactions between elements, and that they be controlled by a single entity with the authority to flow them down, allocating requirements to and ensuring their implementation by the constituent elements. Despite the difficulties, systems-of-systems efforts yield significant payoff when they take full advantage of the different systems’ complementary strengths.

A final obstacle faced by those working on the system-of-systems is the difficulty of testing all of the component systems together. One complication is that all of the systems may not yet be developed and testable in a finished form. Another challenge is the logistical difficulty in bringing together all the needed units, even for fielded systems. The need for high-quality simulations at varying levels of fidelity becomes quite apparent as one considers how to test the system-of-systems. An integral part of each system-of-systems effort described in this article is the reliance on appropriate models and simulations combined with real-world system testing as appropriate. Whereas full-scale testing of real systems in realistic environments must be done at some point, verified and validated models and simulations of appropriate fidelity are an integral part of systems-of-systems development at all stages. Like the need for a single entity to define and allocate requirements, it is important for one organization to be responsible for verifying that the concepts being developed and the final system-of-systems satisfy those requirements. An effective testing and evaluation program, supported by appropriate simulations at the right levels of fidelity at different points on the systems engineering spiral, is vital to the success of any system-of-systems.

CONCLUSIONS

Three examples of systems-of-systems engineering of current and future air and missile defense capabilities and systems were described to illustrate key elements of the systems engineering life cycle. We highlighted the challenges and complexity of concurrently engineering multiple sensors, weapons, and combat systems that encompass modern air and missile defense capabilities, especially when these systems are not collocated on the same units. One of the key tenets in successfully executing this form of complex systems engineering is effectively determining the overall system requirements and allocating the performance requirements across the various systems comprising the broader system-of-systems.

Depending on the complexity of the system and the maturity of the elements (when dealing with legacy elements in an overall architecture), this activity can involve M&S at various levels of fidelity, underpinned by concept experimentation, prototyping, and develop-

mental testing. Without this level of disciplined systems engineering process, complex systems often fail or need expensive rework as the design is iterated to accommodate misunderstood requirements.

In some of the examples described in this article, such as the way-ahead studies, the systems engineering analysis informs large-scale acquisition decisions that have far-reaching implications in system cost and performance that may not be realized for many years to come. It is just as important that this analysis be rooted in

the same systems engineering discipline as those efforts leading to a near-term design.

REFERENCES

- ¹Klingaman, W. K., *APL—Fifty Years of Service to the Nation: A History of the Johns Hopkins University Applied Physics Laboratory*, The Johns Hopkins University Applied Physics Laboratory, Laurel, MD (1993).
- ²Booch, G., Rumbaugh, J., and Jacobson, I., *The Unified Modeling Language User Guide: Addison-Wesley Object Technology Series*, Addison-Wesley Professional, Reading, MA (1998).

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