Systems Engineering of Air and Missile Defenses

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In the Air Defense Systems Department, systems engineering is a way of thinking. More than a "process," the systems perspective drives our approach to solving emerging air and missile defense problems as the threat becomes more advanced and the tactical environment more complex. This perspective and the requisite tools have evolved with the increasing complexity of those systems. In this article I describe the systems approach to the development of missile defenses and cite recent examples illustrating the associated activities.

THE SYSTEMS ENGINEERING PERSPECTIVE

The scientific method, with its methodical and logical order, has been widely used for centuries. As scientifically developed and engineered devices have evolved into complex systems with interacting elements, a systems engineering approach has arisen that is analogous to, and a derivative of, the scientific method. A diagram of the scientific and systems engineering thought sequences is shown in Fig. 1.[1] The systems perspective has been recognized and articulated primarily in the latter half of the 20th century, with its greatest impetus from World War II. Because the Air Defense Systems Department (ADSD) carries forward the APL legacy of the development of the proximity fuze from that era through evolution to modern guided missile defense, the Laboratory's systems engineering perspective has evolved with the emerging national recognition of this discipline. In fact, the ADSD mission statement is steeped in the context of systems-level thinking to solve complex problems.

Before describing how systems engineering is applied to air and missile defense, I first briefly describe what constitutes a good system and the corresponding systems engineering perspective and development methodology. A system is considered to be "interrelated components functioning together toward a common objective."[1] The practice of systems engineering is "an interdisciplinary approach toward methodical realization of a successful system." Finally, a successful system is one that meets the users' needs; interfaces with, and complements, the operation of related systems; functions over the range of exposed environmental and operational conditions; and can be adapted to future needs, environments, and interfacing systems.[1]

Systems engineering is a discipline necessary to produce a successful system. The logical sequence of generic systems engineering steps is shown along with the scientific method in Fig. 1; this is a way of thinking through any phase or level of detail during the development. The system development cycle uses this methodology, from system conception to answering a need through system realization. Why is a methodical, interdisciplinary approach needed? A caricature of a missile design as

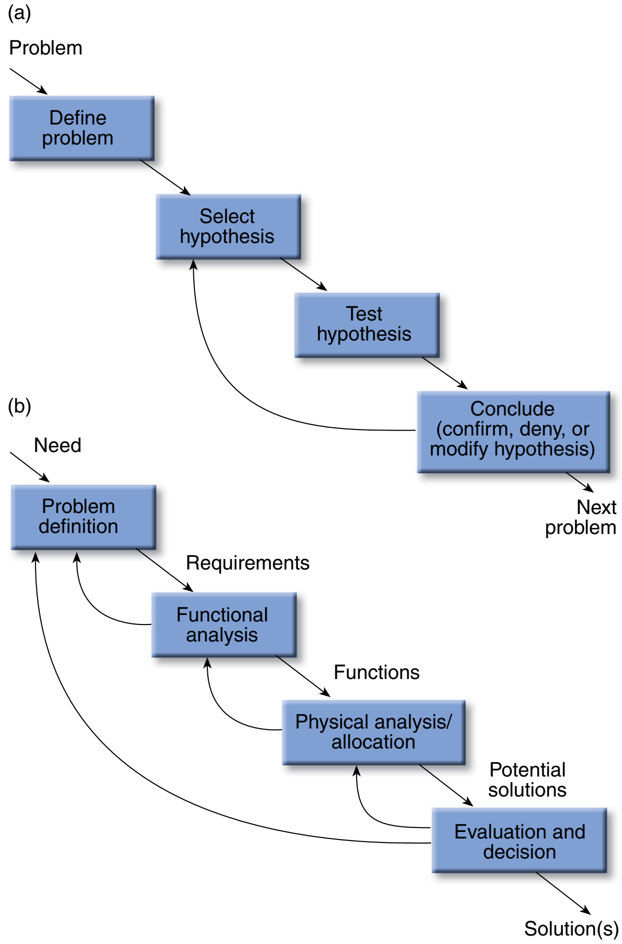

Figure 1. Scientific (a) and systems engineering (b) approaches. The scientific method of hypothesis posing and testing is analogous to the systems engineering method of system element synthesis and validation.

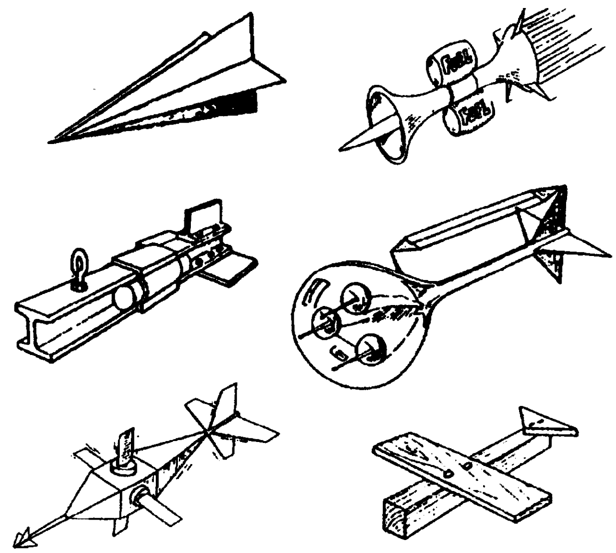

Figure 2. Specialists' whimsical perspectives of a missile system. Each specialty might have a different viewpoint about a system centered on unique expertise and technology. A systems engineer must perform from a balanced perspective, giving appropriate attention to each specialty, often in conflict with one another for resources and requirements satisfaction.

viewed by various specialists[1] illustrates the need for a multidisciplinary approach (Fig. 2). Clearly, each expert has a unique perspective about the system and the relative importance of his or her special contribution and, therefore, about decisions concerning the priority of allocations. Systems engineering must bring this expertise together to develop a balanced system where the components and technologies are appropriately allocated and cost and risk are contained. Within ADSD reside specialists in such fields as control theory, aerodynamics, communications, software engineering, and microwave and optics theory. There are also combat systems engineers who provide analysis and engineering contributions to blend these disciplines. Many times, specialists choose to evolve their careers toward a total systems perspective. Also, many specialists have developed a keen systems perspective, themselves, from long experience. These specialties are included in a number of articles in this issue, but they are viewed for their contributions to their respective total systems.

Why is an air/missile defense system considered complex? Figure 3 depicts air defense elements in a battle force. Each element can be considered as an interfaced subsystem in a force-wide air defense "supersystem." Yet each element is, itself, a system. Figure 3 illustrates both perspectives. The components of the combatants interact in a complex manner. For example, the Cooperative Engagement Capability (CEC) sensor network allows the computers controlling the radars of different ships and aircraft to interact to maintain tracking of targets. The Aegis ship's weapons control computer may use the radar return data of the target from another Aegis ship to develop Standard Missile (SM) midcourse guidance commands. The commands are uplinked via the launching ship's Aegis SPY-1 radar to a receiver in the missile for use in its guidance computer. Thus, the real-time interaction of components among elements of a battle force to support a missile intercept requires the entire force to be treated as a system. The complexity in terms of components, functional intricacy, technology blend, and performance stringency to achieve defense against a variety of threats makes networked air and missile defense among the most complex systems in the world. Articles in this issue further illustrate this point.

How does systems engineering relate to program management? Systems engineers and program managers are partners in the leadership of system development teams. Within the Navy's program offices and program mission offices, program managers and systems engineers provide programmatic and technical expertise for the

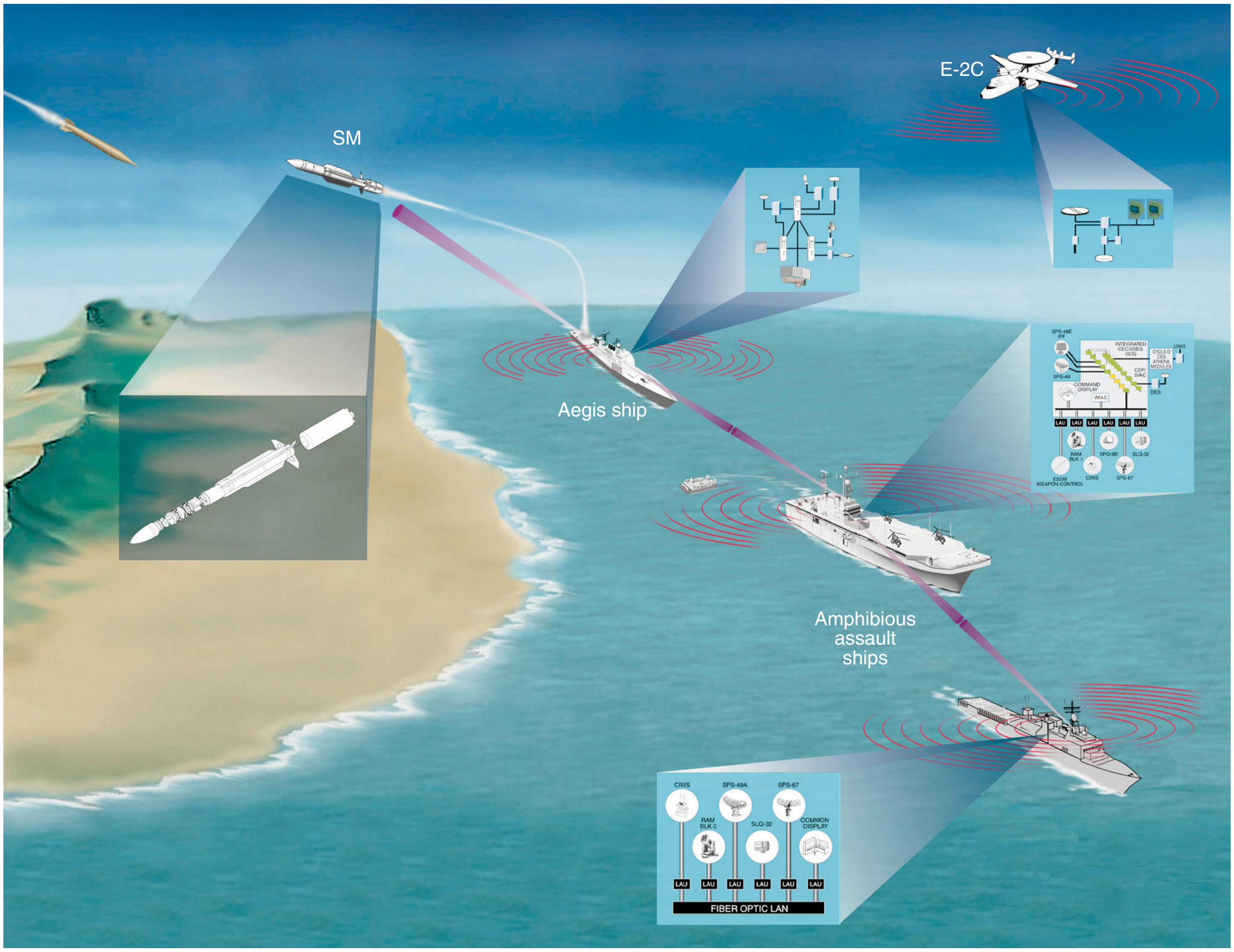

Figure 3. A networked missile defense system is actually a system of systems, with several major systems interfaced as subsystems of a larger force-level system. Shown are an SM, an Aegis ship combat system that guides the SM to its target, an E-2C airborne early warning system that first detects the target and reports via tactical links and the Cooperative Engagement Capability, and amphibious assault ships with the elements of the Ship Self-Defense System in Mark I and Mark II versions featuring integrated NATO Sea Sparrow and Rolling Airframe Missile engagements.

development teams. In ADSD we mirror this arrangement with a matrix organization that provides program and project managers from the programs office and engineering teams from the technical groups.

Increasingly, chief, systems, and lead engineers are being formally designated, primarily from the technical groups, to complement the program and project managers in leadership of systems engineering tasks. The chief/lead systems engineers and program/project managers work in partnership, in addition to leading the engineering team, to ensure that development is orderly and timely and that sufficient resources are provided. As team co-leads, their functions must overlap somewhat so that each recognizes and tends to the needs and resources of the other while they perform their primary roles. As team partners, for example, the systems engineer may develop the technical performance requirements and specifications and lead system modeling and critical experiments to validate the requirements. The program manager provides the programmatic context for these requirements in the key program documents and articulates the underlying programmatic required resources and schedule to achieve them, including the funding, equipment, and facilities for modeling and experiment validations. Some overlap in their roles can occur. For instance, the program manager may have an effect on the technical requirements because of a short schedule or funding constraints. The systems engineer can have an effect on funding and scheduling by articulating and providing evidence of key technical risks that must first be resolved by prototyping or experiments.

Figure 4 illustrates the system development cycle using the Navy Theater Wide (NTW) Tactical Ballistic Missile Defense System as an example. APL was recently designated the Technical Direction Agent for this system, i.e., APL has been given the responsibility of technical oversight for the success of the system and its upgrade evolution. NTW is developed as a system even though it is part of the more encompassing ship combat system and battle force defense network. Part of the missile defense systems engineering challenge is to develop such elements while ensuring the ship and force-level system perspectives.

I will briefly discuss the phases of systems engineering from Fig. 4 as a means of introducing the remaining sections of this article. We begin with the need. Often one or more concepts are explored to determine how to articulate the need. Although the mission need is not specific to the design approach, it may be necessary to convey the need for such conceptual elements as communication or sensing. Operational requirements are introduced in the context of required functions, critical parameters, and effectiveness measures. This generally requires system-level modeling and exploration of the concept in more detail, as well as critical experiments, component developments, or data collections to define and validate the requirements. Conceptual alternatives are assessed to select the preferred approach, and the system requirements, traced to the operational requirements, are developed as the primary basis for the system design.

The system concept and concept of operations form the basis, along with modeling and simulation and risk reduction activities, for partitioning and allocating the system functions and performance to successively greater levels of detail. Iteration and feedback are critical to this methodology because at some level of detail a function may prove infeasible as defined, thus requiring a modification at higher levels to reallocate requirements and functionality. Modeling and simulation can be performed at the various levels of detail required to verify the viability of performance allocations (timing and accuracy budgets and gain margins) for radars and missile guidance in various physical environments; even an entire battle force air defense network can be modeled. Later in this article, I discuss other uses and forms of simulations and models.

ADSD develops and applies models at all levels, many of which have become the Navy standard for their validated accuracy. Prototyping of portions of the system is generally needed to validate that the required performance can be achieved or to validate portions of the more detailed requirements that have been derived from the primary ones. When the partitioning has reached the component level (and has passed a series of design reviews), the components can be engineered,

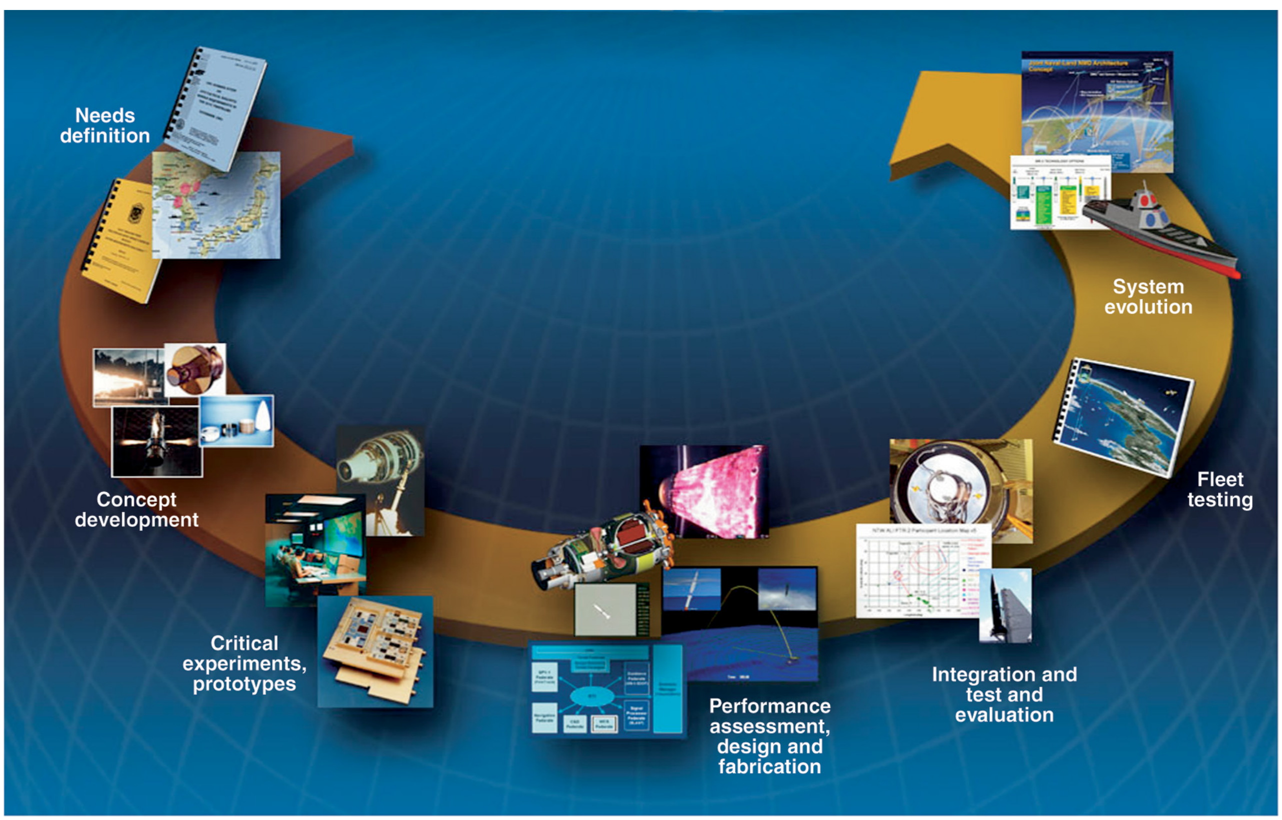

Figure 4. A system development cycle for NTW Tactical Ballistic Missile Defense. The cycle shows systems engineering progression from top-level requirements through concept formulation and assessments; risk reduction activities; development, including design trade-offs, modeling, and fabrication; system element validation and integration; the series of testing leading to a full-scale missile intercept test; and, finally, Fleet introduction, life-cycle support, and upgrade.

fabricated, and tested. Then the bottom-up process of successively integrating and testing components commences in reverse order from the top-down requirements partitioning process. The fabricated components are integrated and tested against predicted performance at the corresponding requirements allocation level, building into subsystems and, finally, the total system. Likewise, testing begins at component integration and builds toward full system-level testing by the intended users, i.e., the Fleet operators, to evaluate achievement of the operational requirements in the representative environments. Systems engineering includes system maintenance and support, as well as planned capability upgrades and modernization throughout the life of the system; these aspects are receiving greater attention as total system life cost is given increasing emphasis.

ADSD has been involved in all phases of systems development. The phases are next described in greater detail, and various examples are provided.

ARTICULATING THE NEED AND DEFINING REQUIREMENTS

A mission need is defined through a continuous assessment of current and proposed capabilities against an evolving threat. It is the basis for establishing a new operational capability, improving an existing capability, or exploiting an opportunity. A mission need statement is very broad and not system specific.[1] For DoD systems, this mission need is documented in a Mission Needs Statement.[2] As part of that document, a convincing case must be made that the need can feasibly be met by existing or demonstrable technology.

After the need is identified, critical operational requirements must be developed. These generally are in some context of the expected technical approaches' fundamental properties so that meaningful critical functions and performance parameters can be defined. For example, it would likely be understood (based on modeling, experimentation, or leveraging of existing systems) whether a new system may require a new sensor or communications element. As a result, a radar or communication range may become a key performance parameter in an Operational Requirements Document.[2] This may be nearly coincident with an analysis of alternatives (AoA)[3] from which an initial larger set of concept candidates is reduced to a small set of preferred cases. Critical experiments and prototype tests may also be required to validate the requirements and the feasibility of the concepts. Operational requirements, therefore, are based on alternatives assessments, feasibility experiments, and other means of concept exploration. They include threshold (minimum required) and objective (desired upper bound) key performance parameter values and performance and effectiveness measures. Both technical and operational (user) requirements are provided. It is important that these threshold and objective values be measurable by analysis or tests. ADSD has played a key role in providing technical support for a number of major system Operational Requirements Documents, including those for CEC, SM, Area Air Defense Command, NTW Tactical Ballistic Missile Defense, and the Ship Self-Defense System (SSDS).

DEVELOPING SYSTEM CONCEPTS AND ASSESSING ALTERNATIVES

The previous section indicated the importance of system concepts and alternatives assessments as a basis for defining needs and requirements. In this section I further define what a concept consists of and how it is assessed. A concept is generally known as a set of the following descriptive items:

- A concept of operations description (its use)
- A description of the system functional architecture in terms of top-level block diagrams of functions and elements with corresponding interfaces between them
- High-level models, e.g., equations or algorithms
- Text descriptions of the block diagram items
- Discussions of critical data, technologies, risk areas, and cost factors

With this level of completeness, alternative concepts can be evaluated against each other in the context of a Design Reference Mission (DRM), which describes the threat, geopolitical, and natural operational environments in which the system is expected to perform.[4] The concepts are defined in sufficient detail for top-level performance modeling to reflect expected technical capabilities and cost factors. These are then compared according to weighted criteria to identify potential "best" candidates.

Figure 5 is an example of model development and AoA concepts for the NTW defense missile, the SM-3. The initial assessment concluded that a missile derived from prior SM-2 components with prototype kinetic kill technology and with substantial intercept range for inland protection was the best approach, having scored the highest for the rating criteria. It was assumed, on the basis of critical studies and experiments, that an evolved version of the Aegis Combat System would guide the SM-3. Further definition of the NTW System from the AoA results used more detailed models and the DRM scenarios to evaluate such critical features as missile boost velocity, the ability of the Aegis SPY-1B phased array radar to discriminate warheads from debris, and countermeasures versus modification options. Figure 6 illustrates the features of the NTW DRM. This DRM, developed by APL's Joint Warfare Analysis Department (JWAD) in partnership with ADSD, is necessarily of sufficient detail to allow comprehensive modeling and

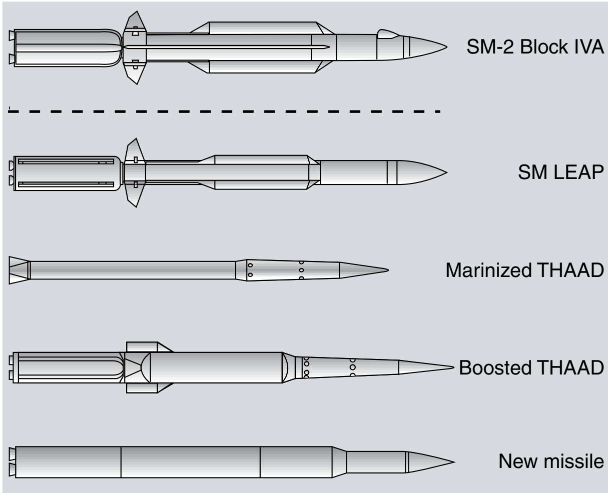

Figure 5. APL played a key role in an assessment of alternative NTW missile conceptual configurations. Of the alternatives shown, the SM LEAP derivative with a kinetic kill capability was determined to be the best approach in terms of cost, risk, capability, and schedule. This alternative was the basis for SM-3.

analysis of NTW System elements. Recent work sponsored by the Navy has resulted in a family of DRMs for various programs that are mutually consistent and part of a "Master DRM."

A system concept is developed from the described activities as well as from results of maturing technology and system studies. Figure 7 is an early illustration of the SM concept of standardization featuring common components in missiles used in the Aegis and the Terrier/Tartar weapon systems of the 1970s. Such standardization provided a major life-cycle cost saving and performance similarity across the Fleet. It formed a basis for system functional requirements and performance requirement allocations to subsystems, risk assessments, and trade-off studies, as discussed later. With the retirement of Terrier and Tartar ships, leaving Aegis as the only area defense system, standardization evolved to the use of modularity in block upgrades to meet advancing threat capabilities.

In the past decade, with Aegis as the only U.S. weapon system using SM-2, standardization has been a primary means of containing cost and risk in block upgrades to more advanced versions or even as the basis for introducing a new mission capability. In the former case, a high degree of commonality exists among the latest block upgrades—III, IIIA, IIIB, and IV—allowing relatively rapid and cost-effective means to address advancing threats. More recently, commonality of the SM series has expedited the development of new Navy missions with the SM-2 Block IVA for Area Tactical Ballistic Missile Defense and the SM-3 for Theater Tactical Ballistic Missile Defense. Standard components even allow timely development of a land attack version known as SM-4.

PERFORMING CRITICAL RISK REDUCTION ACTIVITIES

Because new systems, or major system upgrades, represent a new capability, there are always unknowns in the implementation of the concepts. A set of activities is required for risk reduction to resolve the unknowns by determining feasibility, identifying new phenomena, developing or maturing new types of components and technologies, and learning about new operating parameter regimes. The purpose of risk reduction, then, is to resolve such issues in advance. Such activities include the following:

- Collecting data on critical phenomena not fully understood

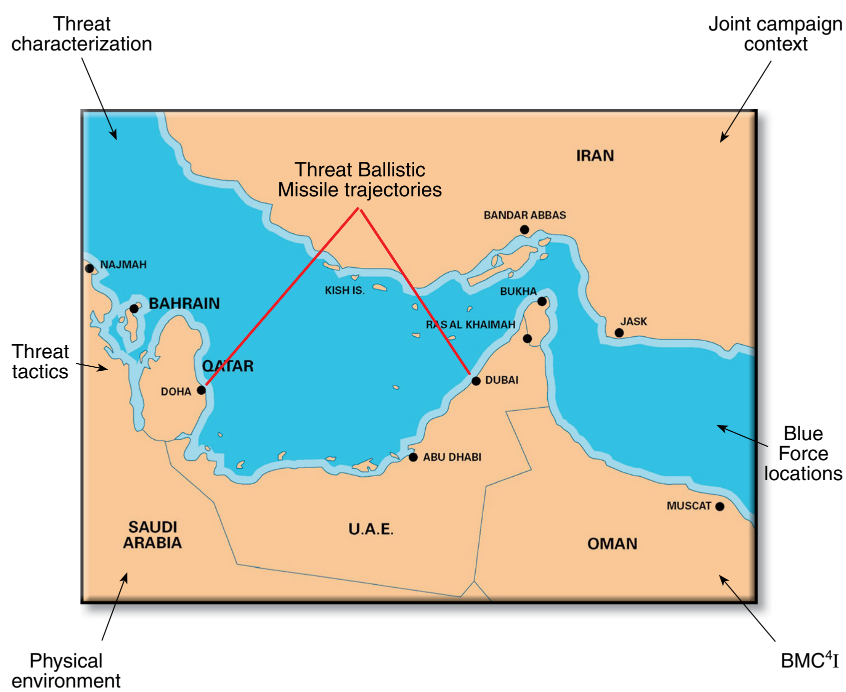

Figure 6. The NTW System will be capable of intercepting longer-range, theater-class, tactical ballistic missiles. To ensure that the analyses and trade-off studies from the development team (from multiple laboratory and industrial organizations) would be consistent, a DRM was developed. Shown is an example operational situation with Joint missile defenses arrayed against tactical ballistic missiles fired from multiple directions and at different times. A variety of conditions are defined that serve as a basis for modeling system element performance versus design allocation alternatives. (BMC^4I = battle management command, control, communications, computers, and intelligence.)

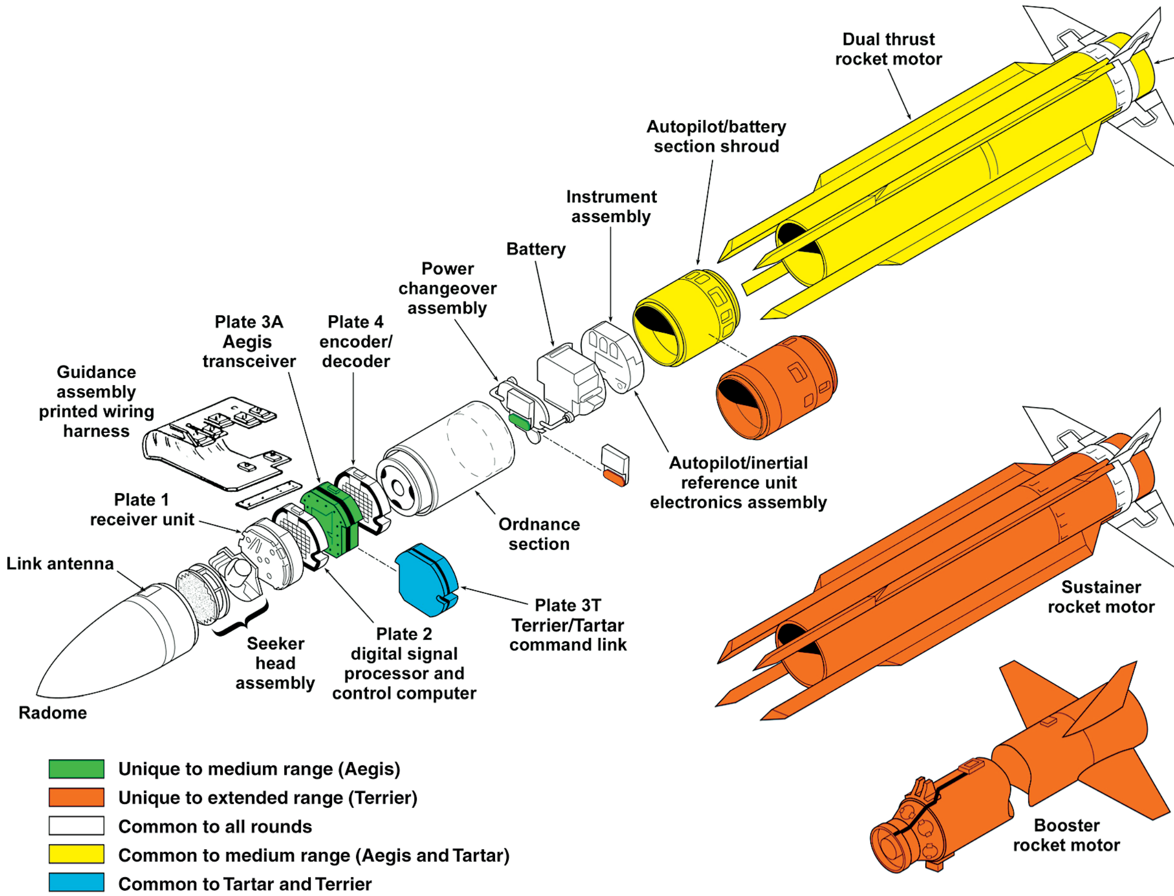

Figure 7. An early SM concept illustration. In the late 1960s and early 1970s evaluations of technologies, costs, and performance requirements led to a system concept definition of standardized area defense missiles.

- Building prototypes of critical components, elements, and/or technologies
- Determining alternative work-around technologies or elements should the risk items fail or become delayed
- Performing appropriate development tests/critical experiments to verify feasibility and performance in expected environments

A critical risk item for SM-2 Block IVA was an infrared window for the seeker terminal homing detector/imager. The window had to maintain sufficient transparency, low distortion, and detector protection in severe flight heating, vibration, and acceleration environments. A set of materials was theoretically identified and experimentally tested, and sapphire was selected. Upon critical prototype fabrication and wind tunnel testing, a number of seemingly random failures occurred. A more detailed theoretical model revealed that the orientation of the sapphire crystal lattice was important; while one orientation met requirements, others did not. This effort was a collaboration with APL's Research and Technology Development Center.

Numerous examples can be cited for CEC as well, including fade margin tests and prototype transmitter and antenna components for the CEC data distribution function and radar data collections for playback into prototype algorithms for the composite tracking function.

In 1996 an advanced concept technology demonstration (ACTD) was conducted in Hawaii in which APL was the laboratory co-lead with the Massachusetts Institute of Technology/Lincoln Laboratory. The demonstration featured the use of CEC to enable an Aegis cruiser to fire a modified SM-2 Block IIIA to engage a target beyond the ship's horizon for the first time using an elevated terminal homing target illumination (on a mountain to represent a potential future aircraft illumination capability). The missile engagement terminal homing was in a range, approach angle, and altitude regime not previously considered in missile design. Theoretical modeling indicated the need for a more frequency-selective illumination reference receiver modification to the missile. However, to reduce the risk of failure in this new over-the-horizon regime, a "captive carry" critical experiment was performed. This captive carry experiment prior to the Mountain Top ACTD (described later) consisted of a missile seeker attached to the wing of a Lear jet to fly portions of the missile trajectory and verify midcourse guidance handoff to terminal homing and seeker lock on to the target. This successful risk reduction critical experiment is described in Ref. 5.

USING MODELING AND SIMULATION

Modeling and simulation are key to all phases of the systems development cycle. In general, a model is a simplified representation of a system or system element or feature. Examples of models are equations, scale models and mockups, and logic flows; some of these can be implemented into computer programs. Simulations generally consist of linked collections of models in the context of a time sequence.

An example is the APL Defended Area Model (ADAM) widely used in the NTW Tactical Ballistic Missile Defense Program to explore combinations of radar range and SM-3 configurations against a variety of targets. Figure 8 illustrates the model elements of ADAM and examples of its output, indicating the area within which a ship could operate and defend a location from a threat direction. The model's ADAM components are a federation of APL and Navy models, and ADAM's development and use are a collaboration between the ADSD and APL's Strategic Systems Department. A new, more detailed, and comprehensive simulation called ARTEMIS is being developed as an

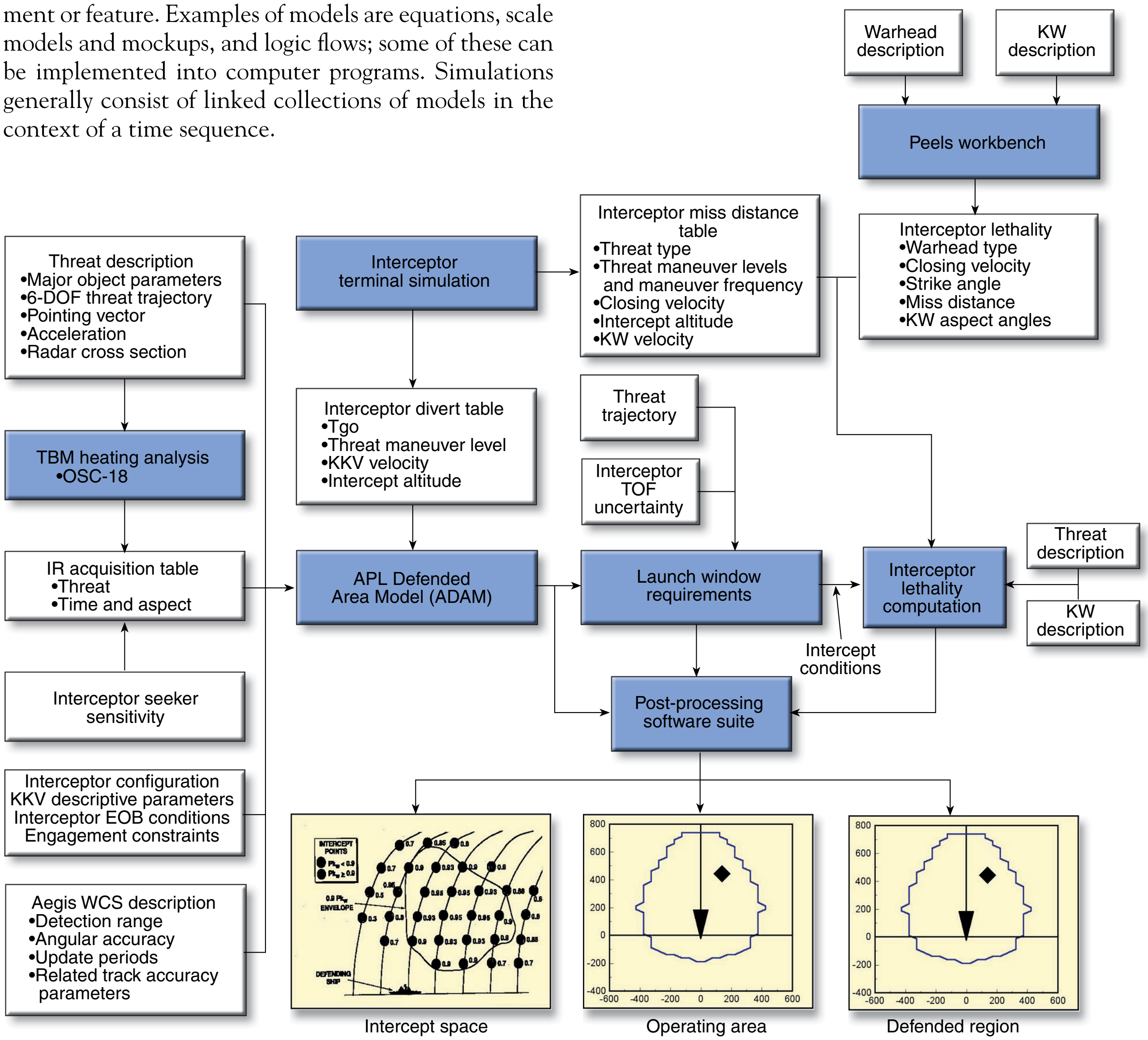

Figure 8. The ADAM allows a wide variety of tactical ballistic missile defense concepts to be evaluated. It includes linked models of sensors, the intercepting missile, command and control features, and kinetic kill vehicle (KKV) homing. Workbench post-processing tools provide visual analysis products (yellow). The blue boxes identify ADAM and associated APL and DoD community models. The clear boxes indicate input and intermediate data. (6-DOF = 6-degree-of-freedom, EOB = enemy order of battle, KW = kinetic warhead, TBM = tactical ballistic missile, Tgo = time to go, TOF = time-of-flight, WCS = Weapons Control System.)

integration of validated detailed models of the entire SM kill chain from target detection through intercept. Models validated by test results can also serve as virtual test vehicles for regions of the performance envelope where actual tests cannot be safely or cost-effectively conducted.

Models and simulations can be used to predict performance and conduct trade-off studies. Trade-off studies investigate technical approaches to meeting requirements at each level of design detail. Modeling cannot be a substitute for real-world testing, as models reflect only a simplified version of the system and its operation and do not fully represent the actual system in its operational environment. There must be a balance between modeling and simulation (since one cannot test for every condition) and testing (since realistic validation is required and expected).

Figure 9 is an illustration of a collection of models linked into a simulation of Overland Cruise Missile Defense (OCMD). One concept of CEC is a form of cooperative engagement known as “forward pass” in which a ship-launched missile flies beyond the ship’s horizon to intercept a target tracked by an airborne radar and guided by data from the airborne radar. A successful ACTD of forward pass occurred in 1996,[5] using prototype and ship elements on a mountain in Hawaii to represent potential lightweight airborne sensors and fire control elements. The success of the ACTD, known as Mountain Top (referred to earlier), led to further interest in defining the advanced elements of such a system for defense of Allied assets far inland. The system concept consisted of airborne detection, tracking sufficiently accurate to support missile guidance, and modified versions of SM, CEC, and Aegis to enable a forward-pass handover of missile guidance from the ship to the aircraft. A virtual follow-on test was performed in JWAD’s Warfare Analysis Laboratory[6] using the simulation of the system network, as shown in Fig. 9c, in the context of a DRM-like scenario over South Korea. The results confirmed and illuminated requirements and corresponding performance for the OCMD capability that could be further developed. They also enabled identification of such issues as determining the appropriate locations of the airborne radar and ship as well as the timing of missile intercepts to minimize terrain blockage.

PROTOTYPING WITH INDUSTRIAL DESIGN AND MANUFACTURING AGENTS

ADSD’s role in system development generally goes through a transition to one of support to an industrial agent in the detailed design, fabrication, and integration phases. This support is often in the form of prototyping to determine the feasibility or to reduce the

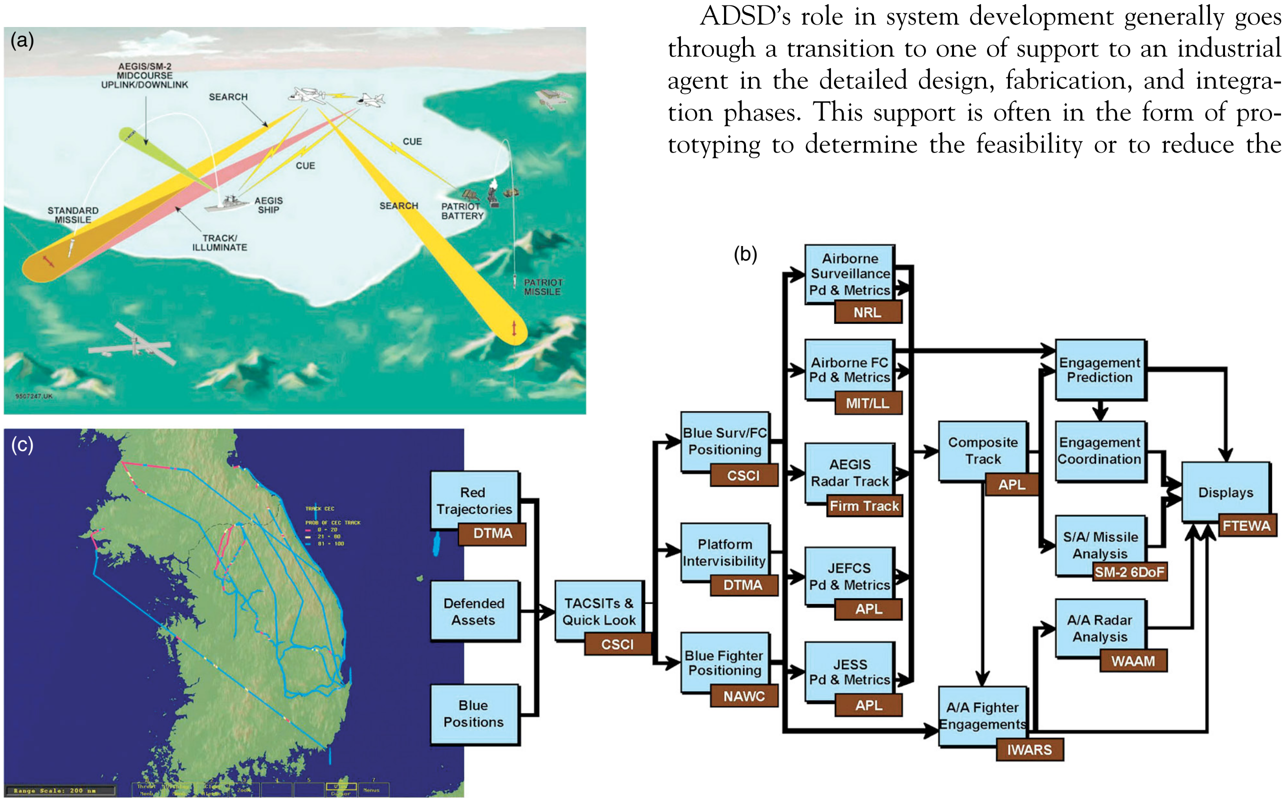

Figure 9. Key elements of a virtual demonstration in the APL Warfare Analysis Laboratory. Shown are the conceptual elements of the OCMD concept featuring (a) a CEC “forward pass” cooperative engagement with advanced E-2C detection and tracking of a target, an Aegis ship-launched advanced SM guided from an airborne fire control suite via CEC and Aegis weapon control, terminally illuminated from the fire control aircraft; (b) a depiction of the high-fidelity models from multiple organizations incorporated to simulate the conceptual system; and (c) an illustration of simulated cruise missile attacks against South Korea for engagement analysis.

risk of a critical component or unproven technology. For such prototyping ADSD generally provides technical guidance to suppliers of the new technology or components. Prototyping has been a key service to the Navy in risk management, feasibility demonstration, and maturing new technology.

ADSD also supports the system development phase of design and fabrication by our involvement in detailed design reviews and software walk-throughs. A design requires definition of all aspects of a system or prototype of system elements down to the component level. Sufficient documentation and engineering guidance must be available to fabricate such components so that they can be interconnected during integration in a fully consistent and matched manner. ADSD helps to ensure that contractors' designs meet these standards.

An example of prototyping and component design is the CEC Data Distribution System in the late 1980s in which a new transmitter was required at a frequency and waveform regime that did not exist in available (late 1980s) components. In partnership with the prime contractor, E-Systems, St. Petersburg (now Raytheon), ADSD developed a prototype transmitter subsystem with special control features and qualified a transmitter tube vendor under a competitive effort. E-Systems' participation during the APL-led prototyping, in turn, led to their successfully developing, in a short time, an improved engineering and manufacturing model of the transmitter that fully met requirements. Somewhat later, APL led the development of solid-state transmit/receive modules for an airborne transmitter/antenna configuration.

USING STIMULATORS FOR SYSTEM INTEGRATION

Just as a design involves decomposition of requirements into allocated elements in a top-down fashion, assembly and integration generally involve a bottom-up approach to successively more complex build-up and test of components into subsystems and, finally, the total system.[1] When certain system elements are not ready for integration, testing can proceed by using so-called "stimulators" in their place, which replicate the inputs and outputs of the missing elements. Two of the best known such stimulators, or element-in-the-loop configurations, are the ADSD-developed wraparound simulation programs (WASPs) for CEC and SSDS and the SM Guidance System Evaluation Laboratory (GSEL).

The WASP approach was originally developed for the Terrier/Tartar air defense systems as a means to ensure that subsystems being developed separately by different organizations would be tested early via WASP interfaces to reduce the risk that the subsystems would not correctly interface. The approach was recognized as necessary for CEC integration testing because the CEC subsystems are developed by different teams, and the Cooperative Engagement Processor subsystem interfaces to different combat systems developed by different companies. A controlled and consistent method was required to pre-test the interfaces before the costly phase of subsystem and combat system integration testing commenced.

The GSEL (Fig. 10) allows the most critical element of the missile, the guidance system (including the seeker subsystems), to be tested in a simulated environment that includes the threat target and the guidance interface to the combat system. This guidance system-in-the-loop test has proven critical to successful missile integration as well as to reconstruction of unexpected results of full-scale missile firing tests for analysis.

For example, the GSEL was recently instrumental in the success of a critical SM-3 test. Confirmation of the test objectives and configuration was followed by the discovery of a software flaw that could have resulted in test failure. The GSEL allows an unprecedented level of test preparation thoroughness when coupled with the validated APL models and the expertise of the staff.

PERFORMING TEST AND EVALUATION ACTIVITIES

ADSD has been intensely involved in all forms of test and evaluation (T&E), including scientific experiments, critical subsystem experiments, prototype element tests, Fleet data collections and exercises, integration tests, test facility operations, flight tests, and full-scale battle force technical and operational evaluations. The legacy is a continuous thread extending from the proximity fuze era and has been much of the basis for valuable hands-on experience and understanding of Fleet operations by the ADSD staff. The design of test approaches and the embedding of data collection and measurement points in a system start at the beginning of the development cycle, and test execution can span the entire cycle, including critical risk reduction experiments. T&E become predominant as an independent activity (from the developers) toward the end of the integration testing and throughout the formal system-level tests.

System-level T&E serves the following purposes[1]:

- Ensuring correct operation in the intended user environment
- Protecting a major system investment by testing early and providing test points for extraction of measurement data that can be examined from the earliest stages of integration
- Gaining confidence and reducing risk of failure by critical prototype and data collection tests
- Demonstrating the readiness to proceed to the next phase of development or testing

The design of a major test is a complex systems engineering undertaking and mirrors the system development

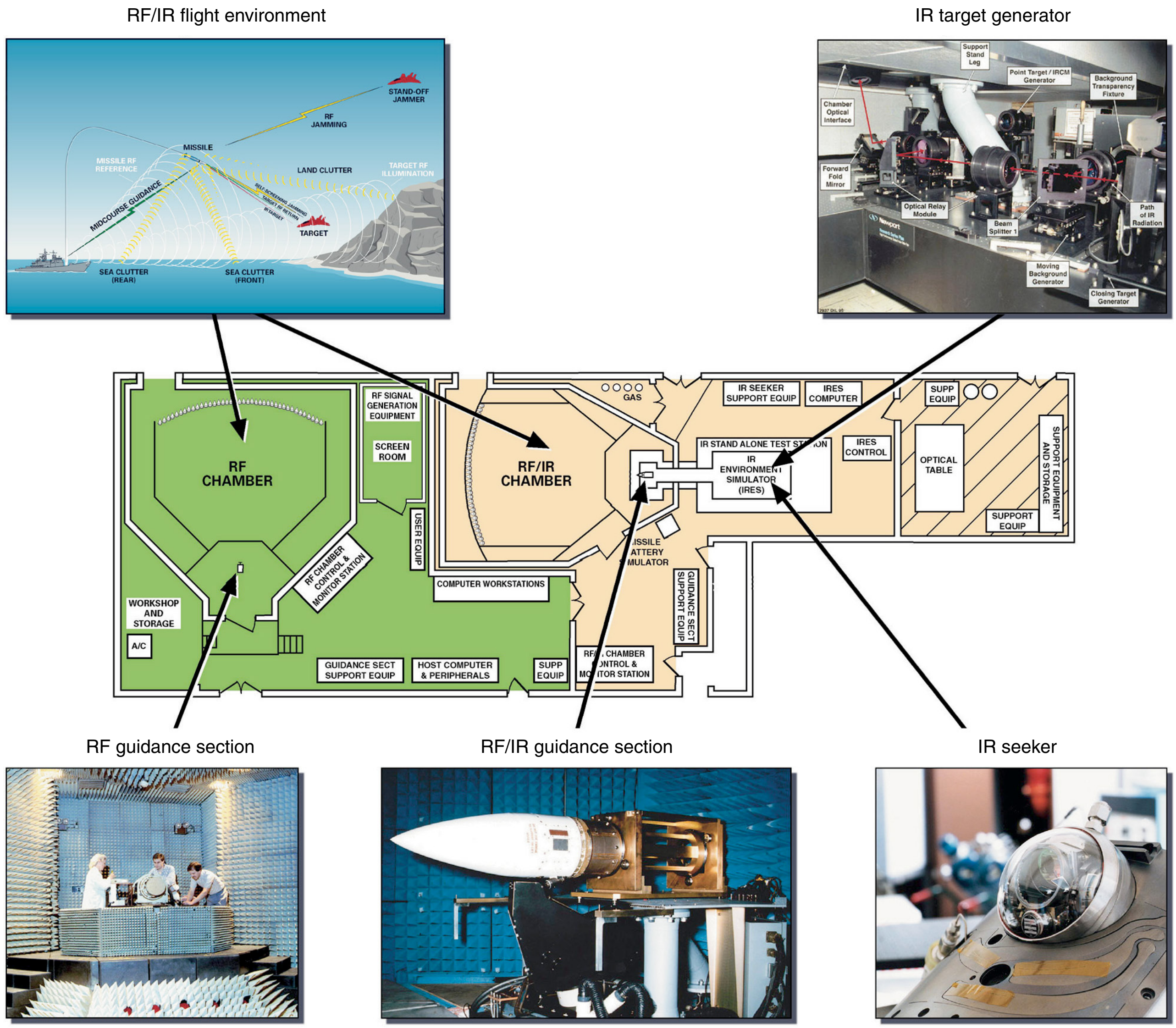

Figure 10. The interior of the GSEL in Building 1. The seeker section of an SM round is mounted and integrated in an anechoic chamber so that the seeker receives simulated guidance commands from computers and specialized interface instruments and its sensor observes simulated microwave or infrared target signatures in the chamber. This hardware-in-the-loop approach has long been a key element in successful SM block upgrade developments.

cycle illustrated in Fig. 4. The test assets representing the threat and operational environment must be specified to simulate the threat and environment defined in the operational requirements. The scenarios must be consistent with the DRM in representing the expected user operation and must provide for relevant performance and effectiveness measures. The spectrum of test scenarios must cover the required operational parameters and conditions. The design of scenarios, including test range safety constraints, generally requires detailed modeling and simulation to ensure that the expected results are valid and that the safety margins are sufficient. The assumptions and inputs to these models can provide insights into instrumentation and test controls as well as their limitations.

Major tests must be thoroughly organized and controlled. Early in system developments ADSD often participates in many of the main test roles, except those of government oversight. Test success requires rigor and thoroughness. In the Mountain Top ACTD described earlier, since an over-the-horizon engagement had never been attempted, an extensive data collection and pretest experiment series was conducted on every element of the system. As mentioned, even the modified missile seeker was flown against the drone target, mounted on a Lear jet, to ensure that sea-surface reflections had been properly modeled and accommodated in the design of the SM rear reference receiver. Virtually every means of testing of every element had been exercised and modeled, other than running the test itself. The very first over-the-horizon engagement resulted in a direct hit as a consequence of systems engineering and corresponding test rigor.[5]

PLANNING FOR SYSTEM EVOLUTION AND THE LIFE CYCLE

The system development cycle and associated activities described earlier are applicable at several stages in the life of a system. A typical system development program goes through several phases. During the conceptual phase, prototyping of some or most of a system may be required to demonstrate feasibility and potential. That was the case for CEC as a new type of system for which there were no precedents. The system development cycle was exercised for the CEC prototype, albeit with tailoring and abbreviation of some of the activities.

The next phase is generally the development of a version of the system that, as a goal, meets the prescribed environmental requirements and is designed to facilitate manufacturing in a production line. This version often has some limit in functionality, for example, to constrain costs on low-risk features at this stage or to demonstrate partial capability before a more complete and sophisticated version of the capability is attempted. This engineering and manufacturing development prototype is more extensively tested against both technical and operational requirements. In many programs it is determined that certain capabilities and performance are not needed during initial operation and that a number of preplanned improvements should be incorporated as a baseline upgrade program. Other reasons for a baseline upgrade would be to extend the service life of a system by introducing new characteristics to keep pace with an evolving threat. For example, Aegis has undergone six baseline introductions since its Initial Operational Capability in 1983, and SM-2 is introducing a Block IV. Often the capabilities of later baselines are far advanced over the initial version. In each baseline upgrade, a portion of the basic development cycle is exercised.

ADSD has been involved in determining required capabilities for baseline upgrades of most Navy air and missile defense systems. SSDS is entering its second block, and CEC is entering Baseline 2. For some programs, such as SM, major changes in technology, performance, and system functions may be made, with lesser changes for adaptation to specific combat systems. Such changes are identified by letters after the block numbers, e.g., IIIA and IIIB. For systems such as CEC, upgrades to software algorithms or subsystem cost reductions, such as array redesigns, are generally featured.

Technology refresh is a significant activity for system evolution. For example, commercial off-the-shelf (COTS) processor cards are used in CEC. These are replaced with newer versions as those versions replace older forms on the commercial market. APL has played a key role in designing the system to readily accommodate new COTS products. A transparent software service layer between the applications modules and the COTS processor network was developed to facilitate COTS refresh.

In APL's earlier versions of CEC and SSDS we pioneered the use of COTS. We found that, in return for supporting the commercial vendors in their beta testing and debugging of new products while we benchmarked the capabilities of candidate products in parallel, the commercial companies were willing to add features to their products that would benefit the Navy systems (even though the Navy is a small client compared to the commercial market). Thus, our involvement influenced the commercial product. More recently, we have pioneered the introduction of commercial, solid-state, microwave module technology into the CEC phased array antennas as a cost-reduction measure. We have also begun a collaborative effort with Raytheon and the National Security Agency to develop anti-tamper protection of the COTS processor and COTS-based software for CEC. APL is prototyping modified COTS processor components and protective software and software load features. These will serve as a design basis for the next Raytheon production version. These activities have, over the years, relied on the technology and manufacturing base of APL's Technical Services Department.

ADSD, with JWAD, has performed life-cycle cost and reliability analyses at the beginning of new system efforts or baseline upgrades. These are used not only as part of AoA concept selection but also to specify reliability and life-cycle costs and, in some cases, to determine design approaches for rapid repair or backup channels to maintain operations during battle. These analyses are also sometimes the basis for determining the number of spares required.

FUTURE SYSTEMS ENGINEERING CHALLENGES

The Navy has established authoritative systems engineering activities to ensure proper system integration of a battle force and all the missions of that force, of which air and missile defense is only one. The principal agencies at present include NAVSEA SEA-053 and the Office of the Assistant Secretary of the Navy for Research, Development, and Acquisition Chief Engineer. We have determined that the fundamental systems engineering perspective, approach, and activities are effective and even more necessary as air and missile defense systems become more sophisticated. We believe, however, that new tools are required to make the systems engineering practices more effective for large-scale systems. The trend is that greater force automation can lead to greater interaction among the computers and links of combatants, and interoperability becomes at once more important and more difficult to attain and maintain. ADSD had anticipated this need in the design of the new Building 26, which houses the System Concept Development Laboratory.

The following new tools are being developed for the described activities and the features that enable them in the System Concept Development Laboratory (Fig. 11):

- Automated visualization of large-scale system diagrams for an entire battle force with database linkages to associated requirements, specifications, models, program offices, design agents, and system equipment and computer programs
- The ability of this visualization to identify inconsistencies, gaps, and shortfalls
- Development of WASPs for remote, networked testing at the development sites and for linkage to systems at different combat system sites to test elements for compatibility and interoperability at the earliest stages of development and integration
- Collaborative specification, design, test, and simulation and experimentation via automated, networked laboratories, facilities, and test sites

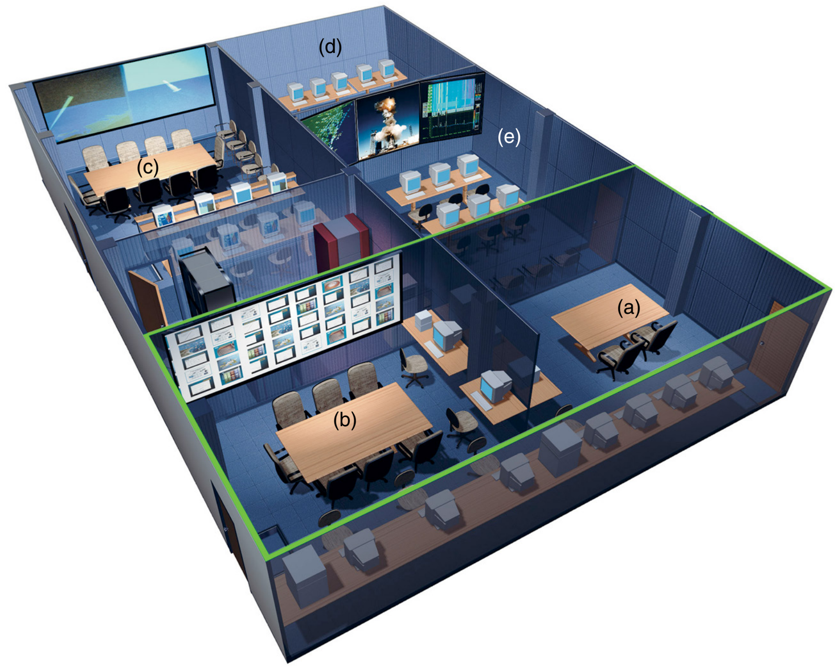

Figure 11. Computer illustration of the new System Concept Development Laboratory featuring (a) an electronic library, (b) a "war room," (c) a visualization laboratory, (d) a force modeling laboratory (with JWAD), and (e) a test participation facility. The laboratory complex is interconnected with other APL laboratories and, via satellite links, to Navy Fleet elements. It is also designed to interface with the merging distributed engineering plant networking being developed within the DoD.

CONCLUSION

We see that the systems engineering perspective and practices are key to the past and future success and accomplishments of ADSD. Trends call for an increased need for rigor, methodical steps, an environment in which critical questions are welcomed, and a process that is open to inspection. New tools are required to ensure that the growing numbers of parameters and conditions can be considered and tracked. With the reduction in the number of experienced engineering staff in military industries and services, the growth of system complexity, and a diminishing tolerance for failure, the long-standing systems engineering tradition and culture of ADSD will be increasingly important in next-generation air and missile defense systems.

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