Naval Theater Ballistic Missile Defense

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The Navy is moving toward deployment of highly mobile and capable active defense forces to provide protection against Theater Ballistic Missiles. Sea-based Navy Area and Navy Theater Wide Theater Ballistic Missile Defense (TBMD) forces can be forward-deployed worldwide, enabling a credible "first on scene" capability without transgressing the territorial waters of sovereign nations. There are numerous technical and programmatic challenges in rapidly developing cost-effective systems with the inherent flexibility for technology insertion and upgrades needed to keep pace with the evolving threat. This article describes how the Navy TBMD programs are overcoming these challenges, the important role of the Mission Program Manager in the acquisition of these urgently needed capabilities, and APL's support of that role.

THE NAVY'S MISSION TO COUNTER THE THREAT

The threat to the security and interests of the United States from Theater Ballistic Missiles (TBMs) is real. The willingness of foreign nations to use ballistic missiles, either as battlefield weapons against opposing forces or weapons of terror against civilian populations, has been demonstrated in recent conflicts (e.g., Desert Storm, Chechnya). Ballistic missiles are proliferating throughout the world at an alarming rate. Over 25 nations have the capability to launch TBMs, and more are seeking to obtain that capability. Consequently, the likelihood of naval forces encountering ballistic missiles is increasing, either as a direct threat or as a threat to assets and population centers that they are called upon to protect. While the majority of currently fielded TBM systems have maximum ranges of less than 600 km and carry conventional warheads, several potential adversaries are pursuing programs to develop more accurate and longer-range ballistic missiles, some of which are nearly ready for deployment or are undergoing testing.

Emerging ballistic missile powers can acquire missile and warhead technologies or complete systems from other nations willing to sell to the highest bidder to support their economic objectives, thereby decreasing the development cycles normally associated with fielding a new capability. Further, these emerging powers do not appear to rely on robust test programs to ensure the missile's accuracy and reliability, dramatically shortening the time between initial flight testing and military use.[1]

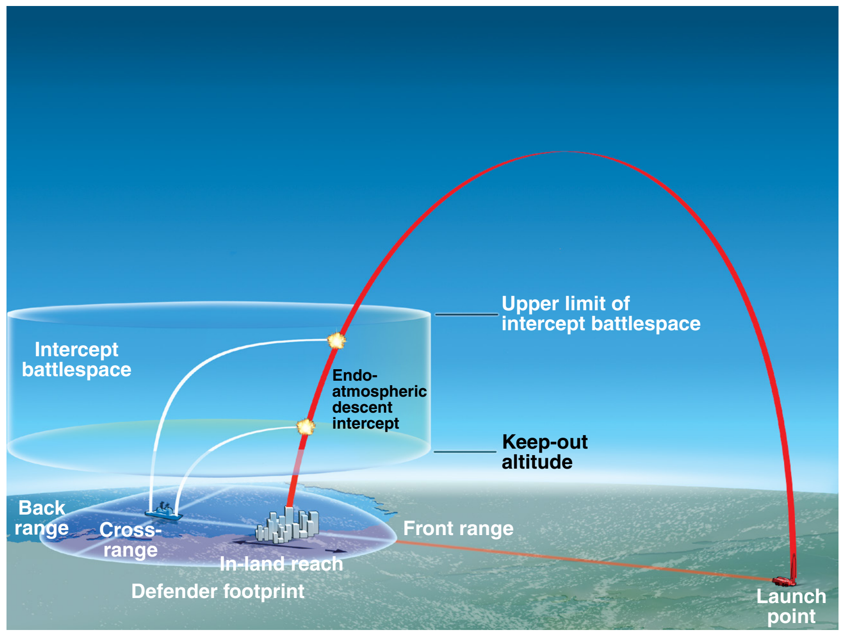
Among the unique challenges that ballistic missiles impose on Air Defense system developers is the variety of possible payloads they may carry. Warheads can be conventional bulk or submunition high explosives or nuclear, biological, and chemical weapons of mass destruction. The biological and chemical agents can also be present in bulk or submunition forms. Adversaries may see asymmetric strategies, e.g., delivering weapons of mass destruction on ballistic missiles, as a means of avoiding direct engagement to overcome U.S. conventional force superiority.[2] An effective Theater Ballistic Missile Defense (TBMD) weapon system must be capable of protecting designated critical assets from the lethal effects of these warheads or negating these threats over an entire theater of operations.

In their 1991 TBMD Mission Need Statement (MNS), the Joint Requirements Oversight Council (JROC) validated the need for active theater missile defenses and further stated that active defenses must consist of "defense in depth" to provide multiple opportunities to negate the threat with differing technologies, resulting in a higher cumulative probability of kill. Defense in depth further prohibits the enemy from being able to counter the defensive system with a single technique. The Sea-Based TBMD MNS, validated by the JROC in 1992, acknowledged that such a capability would be highly responsive and would provide theater commanders with a flexible, mobile means for the defense of amphibious objective areas, debarkation ports, Joint combat and logistic expeditionary forces, and designated inland regions over an entire theater of operations.

In response to these needs and the derived operational requirements, the Navy Program Executive Office for Theater Surface Combatants (PEO(TSC)) and the Ballistic Missile Defense Organization (BMDO) have undertaken the development of the Navy Area and Navy Theater Wide (NTW) TBMD systems as sea-based components of a Joint family of systems (FoS), complemented by the ground-based Patriot Advanced Capability (PAC) and Theater High Altitude Air Defense (THAAD) systems. The mobility of forward-deployed Navy Area and NTW–equipped ships, and their ability to operate independently of foreign government approval, enable a credible TBMD capability to be placed in theater in the early stages of a conflict. The presence of this capability can serve as a deterrent to the use of TBMs. This is particularly important in decreasing the demands on airlift and sealift support for land-based TBMD systems during critical periods of force buildup.

The Navy Area TBMD System is a "lower-tier" system designed to be positioned near defended areas and to intercept TBM warheads within the atmosphere after reentry (endo-atmospheric descent) as shown in Fig. 1a. This capability will address today's predominant short-range threats as well

(a)



(b)

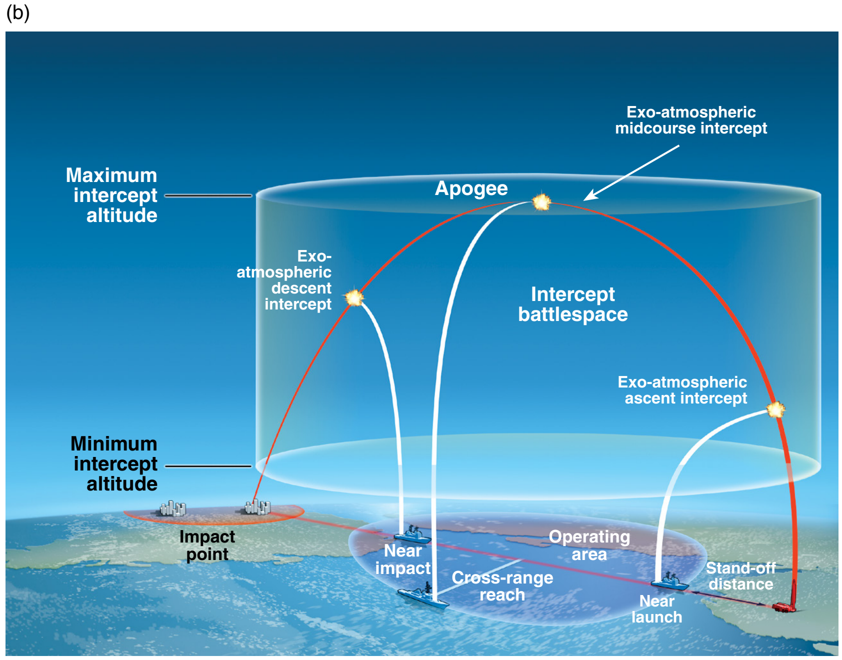


Figure 1. Navy Area TBMD (a) and NTW TBMD (b) battlespace domains illustrating some of the key performance parameters.

as longer-range–capable threats flown at shorter ranges. The NTW System, shown in Fig. 1b, is an “upper-tier” system designed to be positioned along the threat trajectory ground track, from regions near the launch point to regions near the impact point, to support TBM warhead intercepts above the atmosphere (exo-atmosphere) during ascent, midcourse, and descent. The initial NTW capability will address current medium- to long-range threats. Its ability to operate closer to the TBM launch point, coupled with a high-speed missile, gives the NTW System the ability to provide true “theater wide” protection throughout a regional theater of operations.

The NTW System is being developed along an evolutionary path that will enable it to rapidly deploy a near-term capability and maintain effectiveness against countermeasures and improvements to current, emerging, and future threat systems. While the Navy Area TBMD System is not on a formal evolutionary acquisition path, analysis and planning are under way to identify evolutionary improvements to the system to pace the evolving threat. The Navy Area and NTW systems are designed to complement each other, as well as other elements of the jointly developed TBMD FoS, to provide defense in depth. These systems are being integrated onto multimission, multiwarfare ships capable of providing robust air and missile defenses.

The Navy TBMD development strategy is one of program evolution, as shown in Fig. 2. It builds on existing Aegis Weapon System (AWS)–equipped Navy surface combatants to deliver a cost-effective capability to the Fleet using a step-by-step process that keeps pace with the threat. Up to 79 Aegis cruisers and destroyers will eventually be upgraded with a TBMD capability. They will be procured as new construction or as a backfit to existing ships currently deployed. The engineering, training, and logistics infrastructure is already in place and operating.

The Navy has years of experience with battle force Air Defense and has deployed the Battle Management Command, Control, Communications, Computers, and Intelligence (BMC^4I) Architecture necessary to conduct TBMD from the sea. Aegis ships can receive and process cues, vital intelligence, and other tactical information from other ships, land-based sensors, and national sensors. Additional changes to the Command and Control Architecture are being incorporated into the AWS to provide the warfighter sufficient situational awareness and early warning to effectively manage the TBMD mission. The changes include incorporation of processes to accept external cueing from the Defense Support Program, Space Based Infrared System, and other TBMD/Air Defense radar systems (e.g., THAAD, PAC-3, HAWK), the addition of TBMD Link messages, modifications of existing Link doctrine to accept TBM tracks, and inclusion of TBM tracks into integrated Air Defense displays.

Linebacker provides an at-sea platform for testing ship-to-missile interfaces, hardware, and computer programs in operational environments. It allows for early Fleet involvement in system design and testing and an operator feedback process to support the development of TBMD doctrine and employment concepts. The Linebacker computer program is installed and at sea on the USS *Port Royal* (CG 73) and USS *Lake Erie* (CG 70). Modifications of the Aegis AN/SPY-1 radar and associated computer programs enable search, detection, and tracking functions necessary to support Navy Area intercepts by Standard Missile-2 (SM-2) Block IVA. The Program Definition and Risk Reduction (PDRR) Phase of the Area Program culminated in a successful intercept of a Lance TBM target by a prototype SM-2 Block IVA missile in the Demonstration Test Round 1A at White Sands Missile Range. A Milestone II decision to begin engineering and manufacturing development in February 1997 put the Navy Area TBMD capability on the path for the first unit to be equipped in 2003. Ongoing

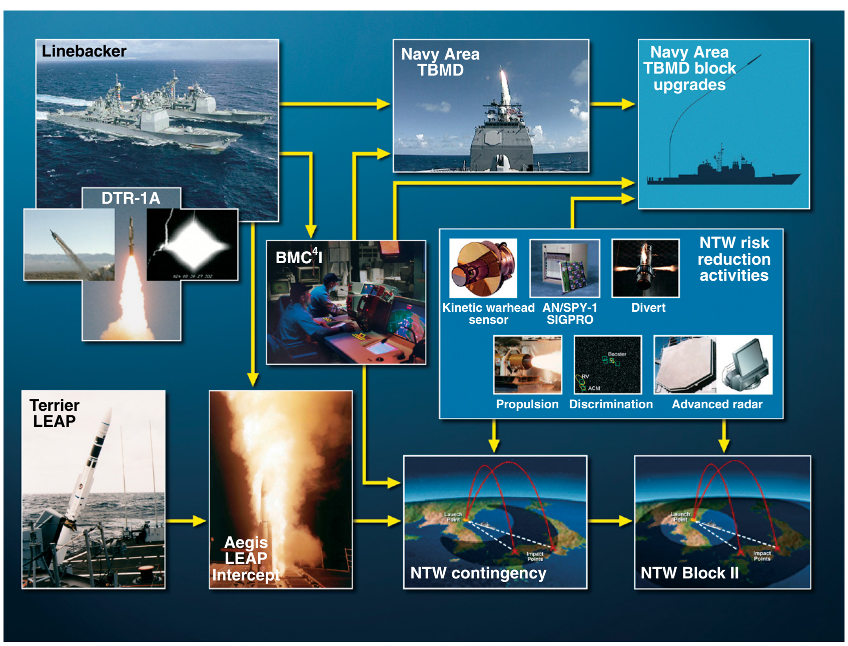


Figure 2. Navy TBMD system evolution from its roots in the Linebacker computer program in 1999, the Terrier LEAP missile firing from the USS *Richmond K. Turner* in 1995, and the Demonstration Test Round (DTR) 1A intercept of a Lance missile in 1997.

risk reduction activities including warhead lethality testing, seeker and fuze testing, and the Joint interoperability exercises shown in Fig. 3 all support the successful introduction of this capability.

The NTW Program builds on knowledge and experience gained from the Terrier Lightweight Exo-atmospheric Projectile (LEAP) Flight Project as it proceeds with demonstrating the technology and ship–missile integration needed for exo-atmospheric intercept of TBMs by SM-3 in the Aegis LEAP Intercept (ALI) Project. Concurrent with ALI, a group of technical risk reduction activities (RRAs) is being undertaken to reduce key technical risks to the overall NTW Program. Development of the NTW Block I System follows from ALI and RRAs, further building upon AWS and BMC^{4}I modifications by the Area Program. Technology advancements and additional AWS modifications planned for the NTW Block I Program may, in turn, be exploited in block upgrades to the Navy Area TBMD System to provide improved capabilities that pace the threat. The success of the NTW Block I Program, accompanied by further RRAs and NTW advanced radar prototypes, forms the foundation for the NTW Block II System, which has increased engagement range and enhanced discrimination, giving it the ability to counter the longer-range more sophisticated threats projected for the future.

THE CHALLENGES

Navy Area Ballistic Missile Defense

The Navy Area Program retains all the simultaneous warfare capabilities (air, surface, subsurface, and strike) included in the previous Aegis baselines. Changes to the Aegis AN/SPY-1 radar are required to allow detection and tracking of TBMs having faster, higher flying, and longer-range trajectories compared with the anti-air warfare (AAW) threats for which the radar was originally designed. These changes were made without increasing the total output power of the radar; rather, special high-energy waveforms were developed and an adjunct linear search and track processor was added to process the returned signals. These new waveforms, when combined with improved Doppler processing, provide better resolution of closely spaced objects at longer ranges. Additional computer program changes were made to implement special volume search, extended search, and cued search modes to support early detection and tracking of TBMs. These improvements allow better management of radar resources to facilitate the AWS ability to simultaneously support AAW and TBMD missions. A resource planning and assessment tool has been developed and will be integrated into the AWS to give operators an automated decision aid for ship stationing and AN/SPY-1 radar search configurations. The tool

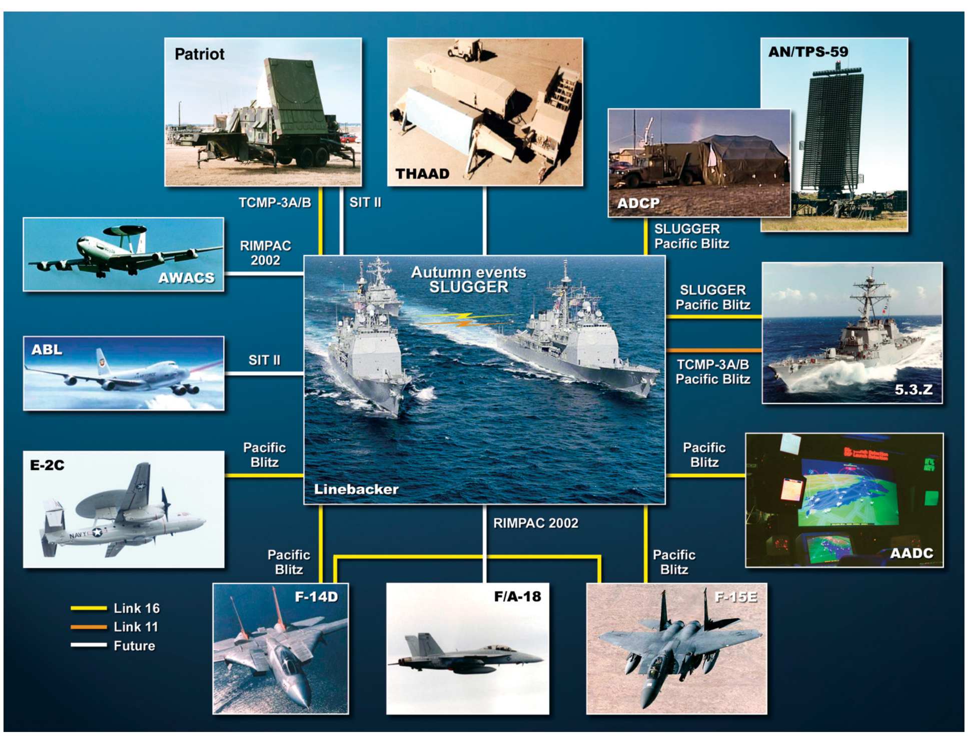


Figure 3. Progress in the demonstration of Joint TBMD interoperability. Early use of the Linebacker computer program during TBMD flight test events will uncover interoperability-related issues and lead to improved BMC^{4}I design.

uses such inputs as anticipated threat types, expected launch areas, and assigned defended areas, and also draws upon technical intelligence databases that characterize the threat and environment.

The Navy Area TBMD engagement sequence is shown in Fig. 4. One major challenge in defeating TBM attacks is discriminating the warhead, whether still attached to the booster or separated as a reentry vehicle (RV), among all the objects associated with a particular TBM launch event. The Navy Area TBMD System relies on AN/SPY-1 radar data to discriminate and select the threat payload. This process is made increasingly difficult when atmospheric drag causes target maneuvers or breakup to occur, whether intentionally as a countermeasure or unintentionally because of airframe instabilities and excessive structural loads.

The SM-2 Block IVA design is based on the SM-2 Block IV Extended Range AAW missile now in low-rate initial production and deployed on Aegis cruisers and destroyers. Block IVA incorporates a new side-mounted imaging infrared (IR) seeker and a new active radio-frequency (RF) adjunct sensor. The IR seeker is used for terminal homing guidance, and the two sensors together provide the angle and range measurements needed to guide the SM-2 Block IVA to a direct hit. The measurements are also used by the new "forward-looking fuze" to calculate the blast fragmentation warhead fuzing solution for near-miss encounters.

The AN/SPY-1 radar tracks the SM-2 Block IVA as it flies toward the predicted intercept point, while the AWS provides midcourse guidance commands via a ship-to-missile uplink. After the AWS discriminates the lethal object using AN/SPY-1 measurements, the guidance track is switched, if necessary, to redirect the missile. The SM-2 Block IVA is guided to a point where its side-mounted IR seeker can detect the primary object and associated objects in the threat complex. The AN/SPY-1–derived missile-to-threat line of sight (LOS) is used to point the seeker to acquire the threat complex in the seeker field of view (FOV).

Autonomous terminal homing by the missile can begin after target designation. The long detection and tracking range afforded by the IR seeker allows sufficient terminal homing time for the SM-2 Block IVA missile to adjust its flight path, using aerodynamic control surfaces, to put it on a collision course with the threat. Proportional navigation is used for final guidance, whereby the Guidance and Control System strives to maintain a constant LOS bearing until intercept. In shaping the SM-2 Block IVA trajectory, a trade-off is made between the desire to approach the threat head-on for optimum warhead lethality and the desire to give the IR seeker a broadside view of the threat for improved terminal guidance to the desired aimpoint.

The terminal homing accuracy of the SM-2 Block IVA allows the Navy Area TBMD System to achieve a significant fraction of direct hits for many TBM threats, but not in all cases, particularly if the threat is maneuvering. For those near-miss encounters, the SM-2 Block IVA fragmentation warhead provides the needed lethality. This robust approach to lethality makes the Navy Area System unique among the BMDO family of TBMD systems.

The challenge presented by the high closing velocities encountered in Navy Area TBMD engagements is answered by precisely timing the warhead detonation in order to place sufficient fragments on the TBM payload. The optimal burst time is determined by the forward-looking fuze, which uses highly accurate IR seeker measurements, combined with measurements from the RF adjunct sensor transceiver. Live fire lethality testing performed by the program has provided a high level of confidence that the SM-2 Block IVA fragmentation warhead will effectively negate TBM threats, including those containing submunitions. Retention of a fragmentation warhead also preserves lethality against other air-breathing threats, an essential capability in this dual-use missile (AAW/TBMD).

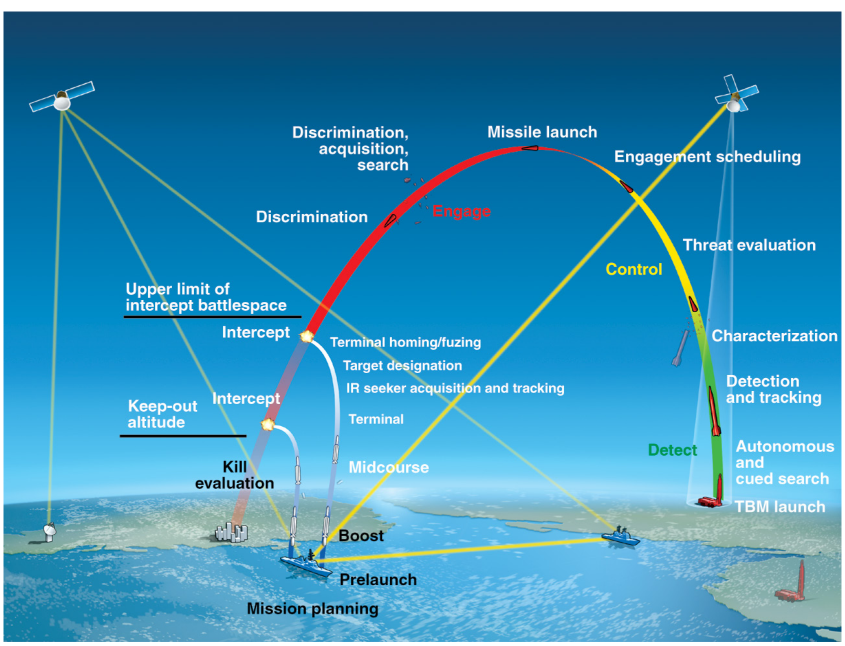


Figure 4. Navy Area TBMD engagement sequence.

Navy Theater Wide Ballistic Missile Defense

The NTW mission introduces a different set of challenges to system developers. To achieve protection of much larger regions of the theater from a single ship, the battleground is taken into space (the exo-atmosphere), where medium- to long-range TBMs spend a greater portion of their transit time. The ability of the NTW System to be positioned along the TBM ground track, from near launch to near impact and at significant cross-range, provides greater freedom of movement for the ship and greater flexibility to be positioned in a manner that is best suited for the geographic location and operational objectives. For example, in situations where the launch region is relatively small compared to the defended region, an NTW ship position close to suspected launch regions enables engagements of TBMs during their ascent phase of flight, thus allowing a single ship to negate threats having large variations in flight heading. The high-velocity SM-3 missile, coupled with early detection and tracking of the TBM by the AN/SPY-1 radar, enables this exo-atmospheric intercept capability over large ship operating areas.

For ALI and Block I, SM-3 uses the proven Mk 72 booster and Mk 104 dual-thrust rocket motor (DTRM) for the first and second stages. Attached to the DTRM are a newly developed staging assembly and a dual-pulse third-stage rocket motor (TSRM) with an added third-stage guidance section. The TSRM provides the added missile velocity to achieve exo-atmospheric flight, and the two pulses allow flexible energy management to tailor the SM-3 trajectory and flight time to match a specific TBM engagement. The fourth stage of SM-3 consists of the kinetic warhead (KW), which is protected during atmospheric flight by a removable composite nosecone. The KW is designed for spaceflight, and for ALI and Block I uses a Solid-propellant Divert and Attitude Control System (SDACS) to give it pointing ability and maneuverability for terminal homing on the TBM threat.

The NTW battlespace encompasses a wide variation in possible ship positions, intercept altitudes, TBM threat and countermeasure characteristics, and closing conditions between the SM-3 and the threat. For the initial Block I capability, the required probability of threat negation for the NTW System is to be achieved in a single shot, though the depth of fire of the systems provides a significant shoot-look-shoot capability. One challenge in developing this capability is in the design of engagement logic and fire control policies, which give the system a robust capability across the entire battlespace, allowing it to achieve a high probability of single shot engagement kill (P_{ssek}). For each NTW engagement, the AWS must identify and characterize the threat, assess the engageability of that threat, and schedule the SM-3 launch. The launch scheduler algorithms must consider, among other things, the duration of the launch window, coordination among other firing units that may have a shot opportunity, spacing of launches in the TBM raid environment, and management of AWS radar resources. A notional NTW ascent phase engagement sequence is shown in Fig. 5.

Critical to achieving successful engagements by the NTW System is closure of the fire control loops during each phase (prelaunch, boost, endo-atmospheric midcourse, exo-atmospheric midcourse, and terminal) of the engagement. This requires a fully integrated, closed loop feedback process between guidance processors, missile control and monitoring systems, and navigation and tracking sensors. It further demands reliable communications and interfaces among these elements to maintain the critical flow of information needed to carry out the processes. The guidance algorithms and closed loop processes can vary for each phase. For ALI and Block I, the SM-3 is command-guided by the ship during endo-atmospheric midcourse via a ship-to-missile uplink, and is inertially guided using inputs from the ship on threat and missile tracks during exo-atmospheric midcourse. Critical to the successful implementation of the fire control design is management of the conditions required for successful handover from one phase of the engagement to the next. Of particular importance is the handover to the KW for the terminal phase, which requires (1) that the TBM payload be contained in the

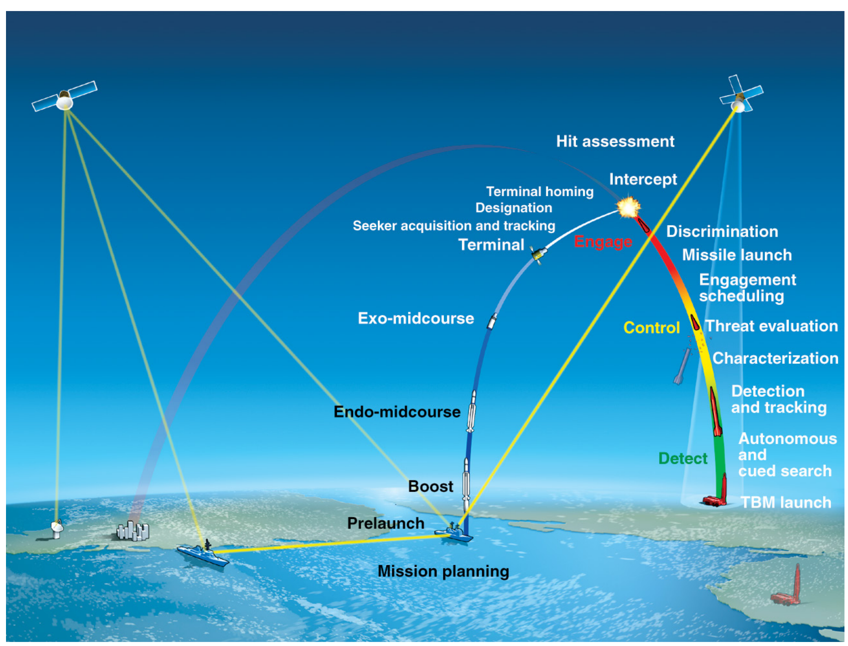


Figure 5. Notional NTW ascent phase engagement sequence.

KW seeker FOV when directed to look toward the AWS-designated guidance track point, and (2) that the miss distance of the KW trajectory to that of the TBM payload trajectory be sufficiently small so that the KW divert capability can remove the miss in the time remaining to intercept. Accomplishing these conditions requires careful balancing of NTW system errors and uncertainties in the behavior of the threat.

Subsequent to handover from the AWS, the KW must achieve target capture to begin its autonomous terminal homing on the TBM payload. The KW achieves long-range detection by using its forward-looking IR seeker, which operates in the long-wave IR band. Additional information in the handover message is provided for other tracked objects expected to be in the KW seeker FOV when activated. To make use of designation and discrimination information provided by the AWS, the KW attempts to correlate the object tracks in its FOV with the AWS tracks. Target capture is achieved after completion of KW discrimination and selection of a seeker guidance track for terminal homing. The KW uses zero-effort-miss predictive guidance for terminal homing. This algorithm applies estimates of miss distance (assuming no divert) at the time of closest approach and the associated time-to-go to determine the net divert thrust direction and duration needed to drive the miss distance to zero for a direct hit of the TBM payload. As the image of the threat becomes resolved by the IR seeker, algorithms are employed to to determine the desired aimpoint for achieving high probability of kill given a hit within small miss distances from that aimpoint. The KW uses reserved divert fuel for its final maneuver to the aimpoint.

The NTW System is "hit-to-kill." A portion of the kinetic energy of the collision is converted into heat, light, and material strain energy upon contact of the colliding bodies. Lethality testing has demonstrated this to be an effective means of destroying TBM warheads when closing velocities are sufficiently high. The AWS schedules engagements and shapes the SM-3 trajectory to exceed minimum closing velocities to meet lethality requirements. The SM-3 KW must further have sufficient seeker accuracy to designate and track an aimpoint on the threat and have sufficient agility in its control system and SDACS to achieve small miss distances from that aimpoint.

A typing function must be performed by the AWS to identify the threat class or specific threat so that *a priori* knowledge of the threat can be fully exploited in performing discrimination and selecting the best guidance policy. The key to exo-atmospheric discrimination is to find a set of "features" that can be related to the physical attributes of the bodies in the threat complex (e.g., size, shape, material, temperature) or to the body dynamics (e.g., spin, tumble, nutation), which distinguish the RV from the other bodies when compared in the domain of the selected multidimensional feature space. In general, the more specific the typing, the more likely the objects in the TBM complex can be separated into distinguishable regions of a feature space, thus resulting in a greater likelihood that the system will be able to correctly identify the lethal object. Typing can be supported by strategic and operational intelligence information combined with observations of the TBM flight profile and trajectory events, such as staging and separation events. The NTW Program is seeking a balanced approach to discrimination, exploiting features in both the RF spectra of the AN/SPY-1 radar and the IR spectra of the SM-3 seeker to provide a robust capability against a wide range of TBM types and associated countermeasures.

The AN/SPY-1 radar measurements of narrowband radar cross-section can be correlated with the relative size and shape of various bodies. Since the measured radar cross-section of the bodies typically varies with viewing aspect and body roll orientation, it is possible to extract information on body dynamics from the observed time variation in these measurements. Testing is also being performed on synthetic wide-bandwidth techniques, whereby the AN/SPY-1 puts out a burst of sequential frequency-stepped narrowband pulses. This capability, along with the associated signal processing, provides high range resolution for obtaining range depth (proportional to object length) information on a tracked object, as well as allowing for earlier resolution of closely spaced objects.

Similarly, SM-3 seeker IR intensity measurements will be a function of an object's surface temperature and emissivity as well as its projected area on the plane of the seeker FOV. While this combines three physical attributes of the object, intensity can be used as a discriminating feature. Also, because of the roll and aspect dependency of the measured intensity, scintillation (the time variation of intensity) can provide additional information on the object body dynamics. Advancements in two-colored IR seeker technology in the NTW Program will allow decoupling of the estimated surface temperature and emissivity-area product. This is particularly important in distinguishing chuffed propellant and IR flares, which may exhibit a similar range of total IR intensity compared with the lethal object, but are generally smaller and hotter bodies.

The Command and Control System to support NTW is built on the existing Navy Area TBMD Architecture. NTW-equipped Aegis cruisers will be interoperable with other theater assets via the Joint Architecture and its respective networks, which include the Joint Planning Network and the Joint Data Network. This will give unit and force commanders the needed information with sufficient timeliness to allow the NTW System to conduct coordinated operations with other TBMD assets in the theater. A number of coordinated engagement schemes are being explored in the NTW

Program that will potentially allow netting of sensors and distribution of weapon control among multiple TBMD units to provide better protection of the theater with fewer assets. As the TBMD System with the earliest opportunity to engage a TBM in flight, it is vital to the concept of defense in depth that the NTW System be capable of quickly assessing the outcome of its engagement and providing that information to the downrange upper-tier (THAAD) and lower-tier (Navy Area, PAC) systems in the event that a second shot is required to negate the threat.

RESPONSIBILITIES

Mission Program Manager Role

The scope of the Navy TBMD programs, which have both been designated as Acquisition Category 1D Major Defense Acquisition Programs (MDAPs), includes design, engineering, production, testing, modernization, and life-cycle management. The Navy PEO(TSC) established the role of a Mission Program Manager (MPM), PMS 451 for Navy Area and PMS 452 for NTW, with the responsibility for system development and deployment, and the delegated authority to assure total systems engineering and program performance. Each MPM has established a Mission Program Office (MPO) with the organization and staffing necessary for the implementation and management of systems engineering, test and evaluation (T&E), risk management, and program planning and control processes.

The MPM serves as the focal point for management planning, coordination, and program execution and is responsible for the development of requisite acquisition-related documentation. The MPM, in coordination with the PEO(TSC), is the program's principal interface to the Acquisition Executive (Director, BMDO), and as such, must ensure the proper representation of budgetary requirements and technical and programmatic issues and concerns. Through a unique reporting relationship,[3] both the Navy Area and NTW MPMs are actually assigned for additional duty to the Director, BMDO, and report to the Director on matters pertaining to Ballistic Missile Defense. The PEO(TSC), under the direction of the Assistant Secretary of the Navy for Research, Development, and Acquisition, has overall responsibility for development and deployment of the Aegis Combat System (ACS). Hence, the MPM must also coordinate with the PEO(TSC) on issues regarding multimission aspects of the ACS and the integration of the TBMD mission. The MPM must also prepare the program for Defense Acquisition Board reviews and approval of program milestones and the acquisition program baseline. Close liaison must be maintained by the MPM with the Assistant Chief of Naval Operations for Missile Defense for matters concerning Navy operational requirements, concepts of operation, and doctrine, and with the Commander Operational Test and Evaluation Force for planning system operational T&E prior to Fleet introduction.

Program execution by the MPM is accomplished through coordination with other PEO(TSC) acquisition program managers and systems engineering activities, as well as with other MDAP MPMs as necessary. The MPM is responsible for translating operational requirements into system performance requirements and developing the functional allocation of requirements to the system elements. These are captured in a System Requirements Document (SRD), which forms the basis for the system functional baseline definition as well as the control mechanism for ensuring proper flowdown of requirements to the allocated and product baselines. Consistent with program guidance and in response to the SRD, Product Program Managers (PPMs) will manage specification, design, development, and manufacturing of the system elements. The PPMs within PEO(TSC) are PMS 400B for Aegis, PMS 410 for surface launchers, PMS 422 for SM, and PMS 426 for radar systems. The Aegis Technical Director (PMS 400B) performs element interface control and system integration with the AWS. The MPM coordinates with the PEO(TSC) Deputy for BMC^4I (TSC(TD3)) to help ensure system compatibility with the Navy's battle management, command, and control systems and to interface with organizations outside the PEO(TSC) organization to implement and control the systems' interfaces to other Theater Air Defense systems and BMDO FoS TBMD systems.

Mission Technical Direction Agent Role

The traditional role of Engineering Agents in support of NAVSEA acquisition programs was to assist the System Manager throughout the life of the program. NAVSEA Instruction 5400.57A, dated 6 December 1985, identified the roles and functions of six Engineering Agents required to provide continuous engineering support from concept and development through production, Fleet introduction, operation, and maintenance. That instruction did not define entities such as a Combat System Technical Direction Agent or a Mission Integration Agent, and the use of agent titles beyond those described in the instruction was prohibited. In July 1999, Instruction 5400.57B broadened the definition as follows: "An Engineering Agent is an organization with responsibilities delegated by a Program Manager and/or Engineering Directorate and technical authority delegated by an Engineering Directorate." This revision appears to have been motivated by the recognition that current and future weapon system acquisition programs would comprise increasingly complex and interrelated systems. The emergence of "mission areas" as the focus for the generation of weapon system requirements makes many of the traditional Engineering Agent roles and individual Product Office functions distinct elements of a more complex system. The revised instruction recognizes this need and allows specific Engineering Agent assignments to be tailored to individual programs or product lines.

The Navy Area and NTW TBMD programs are good examples of very complex systems incorporating existing, modified, and new weapon system elements to address the Air Defense and TBMD missions. The Mission Technical Direction Agent (MTDA) function is to provide the best available technical advice and counsel to the MPO, enabling it to effectively achieve program objectives consistent with overall program goals and constraints as established by the MPM. Such a role is only possible if the responsibilities of the MPM and MTDA are clearly identified to the larger acquisition community and executed consistently. The MPM must ensure that the MTDA is fully informed on the program's cost, schedule, and performance objectives. The expectation for the MTDA is to promote program success through the consistent application of rigorous and disciplined systems engineering principles and practices across all system elements over the program life cycle.

Equally important in the era of "acquisition reform" and downsized program offices is the maintenance by the MTDA of essential research and engineering capabilities and corporate memory. MPO personnel must facilitate relations and the transfer of information among Product Program Offices (PPOs), their Engineering and Design Agents, other government laboratories, and the MTDA. Transfer of information among different PPOs and their Design Agents is one of the most difficult obstacles to overcome and yet is critical to the successful development of very complex systems. If necessary, MPO personnel must also facilitate the timely resolution of issues identified by the MTDA. The interactions and relationships between the MTDA and the various agents and PPOs are shown in Fig. 6.

Several significant organizational attributes are necessary for the MTDA to be effective. The MTDA must be able to act as a trusted agent to the MPM. The candidate organization should have a comprehensive knowledge of current technology as well as legacy

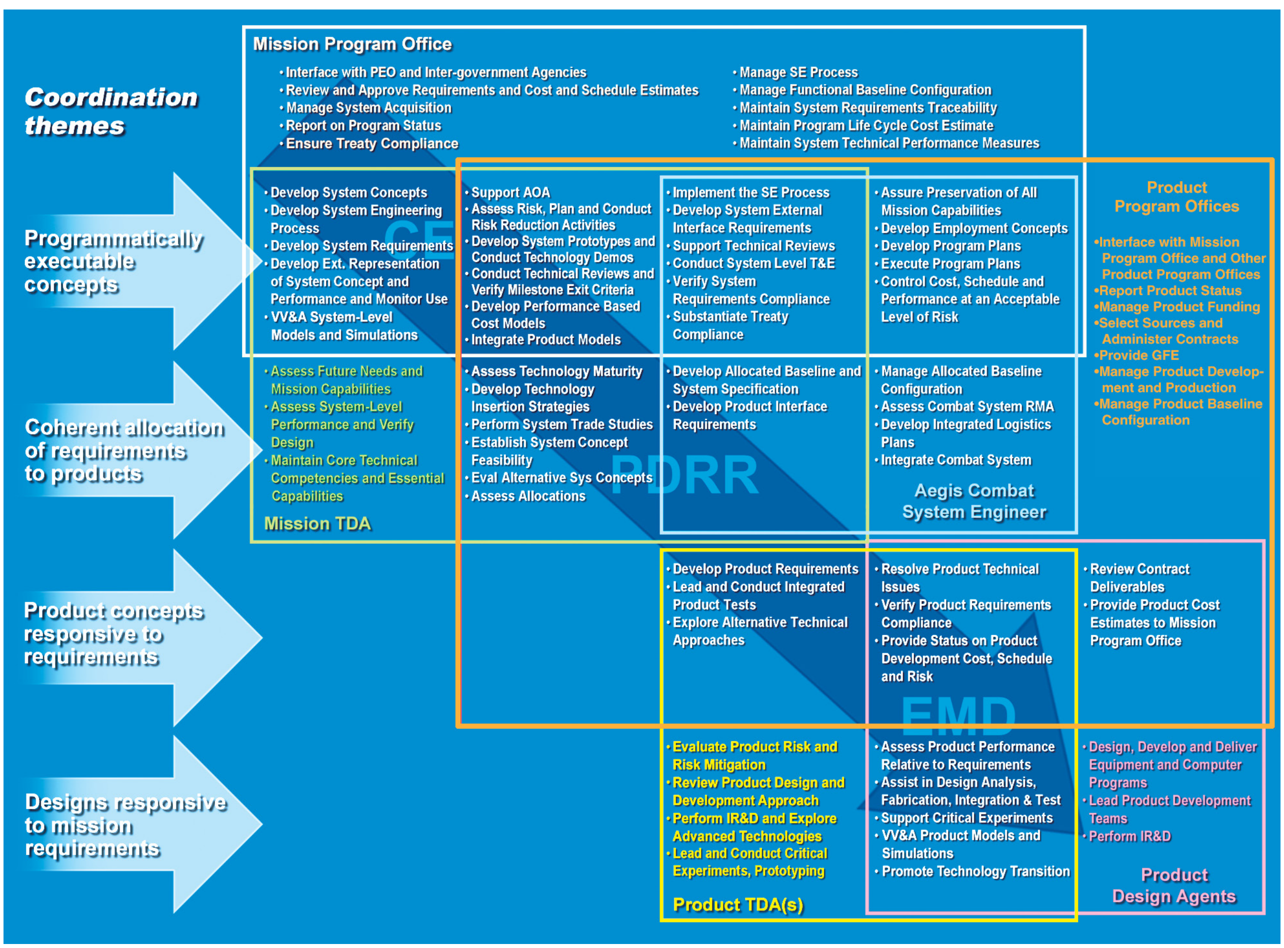


Figure 6. Mission TDA domains and interactions with other program elements from concept exploration (CE) through program definition and risk reduction (PDRR) and engineering and manufacturing development (EMD).

systems. It must be capable of providing independent and objective technical assessments and exhibit leadership in an increasingly complex teaming environment. It must have qualified, multidisciplinary, motivated engineering teams organized such that sufficient human and materiel resources are flexible and responsive to emergent tasking.

APL provides a unique capability combining expertise in system architecture and systems engineering, with specific experience in radars including AN/SPY-1, the ACS, and the Cooperative Engagement Capability. As the TDA for SM, the Laboratory is responsible for the missile's life cycle, from concept development through weapon system integration, production, and Fleet operations. It develops and maintains high-fidelity computer models of AN/SPY-1, SM-2 Block IVA, SM-3, and other ACS functions to conduct engineering analyses of subsystem performance as well as end-to-end system performance. The breadth and depth of APL research and engineering personnel and facilities is a Navy resource resulting from over 50 years of investment.

The Laboratory has demonstrated leadership in coordinating among Program Offices, Navy laboratories, prime contractors, and other contracted support in directing activities to reduce program risk and to enable successful weapon system development. By virtue of its mission and core competencies, APL continues to be a trusted agent and technical advisor to its Navy sponsors. As an organization, the Laboratory is uniquely suited to perform the MTDA function for the Navy TBMD MPOs.

The specific NTW MTDA responsibilities outlined in Ref. 4 include the following:

- Provide leadership in system concept exploration, characterization of operational environment, and definition of system requirements
- Facilitate implementation of consistent and disciplined systems engineering processes
- Perform independent evaluation of system design concepts, technical approach, and development progress and make recommendations to the MPM on technical issues and alternatives
- Lead special studies to investigate problems or probe alternative approaches
- Provide independent assessment of the integrated performance and effectiveness of system elements
- Provide support in system T&E including development of mission requirements and scenarios, mission planning, and analysis; development of target requirements and oversight of the procurement and certification process; and design, development, and integration of specialized target instrumentation
- Assist the MPM in assessing program risks, prioritizing risk reduction activities, and evaluating technology and design maturity
- Perform research, analysis, and experimentation, as appropriate, in high-risk areas to validate technical feasibility or retire risk assessment
- Facilitate a systematic transition of knowledge and technical insight to develop a common understanding of system requirements and program objectives through support of integrated product teams, working groups, and design development teams
- Assist the MPM in ensuring the integrity of the system concept throughout the development process through technical review of specifications and design, and evaluation of system integration and test outcomes
- Perform integrated cost/performance analyses to support programmatic and design trade-off assessments
- Provide leadership in evaluating future mission needs and exploring advanced/evolutionary system concepts
- Maintain core technical competencies and essential capabilities

APL provides technical leadership in these areas for the Area MPM as well. In the next section we describe a number of important activities initiated and being led by the Area and NTW MPOs and supported by APL.

APL-SUPPORTED ACTIVITIES

NTW Concept Definition

Concept definition is the starting point for program acquisition and the responsibility of the MPM. During the Concept Exploration Acquisition Phase of the NTW Block I Program, APL provided technical leadership in requirements analysis, system concept definition, and performance assessment. Systems engineering activities highlighting this phase of the program included trade studies, development of the SRD, and system performance analyses to verify the feasibility of the system requirements. APL led or co-led trade studies covering discrimination, terminal phase handover and target selection, SM-3 seeker alternatives, and operational sequences. The trade studies identified functional and configuration alternatives to support concept selection, and developed functional performance models to support requirements allocation and system-level performance assessments for the concepts. These activities culminated in a System Requirements Review in March 1999, followed in May 1999 by Defense Acquisition Board approval (Milestone I) of the initial acquisition program baseline, and authority to proceed into the PDRR Phase. APL produced a final draft of the SRD for the MPO, which was subsequently placed under configuration control, and published the first version of the System Concept Document.[5] This document provides a high-level description of the NTW mission, the system concept, how the system will be used, and how the system may evolve.

In response to later BMDO guidance, the NTW MPM was charged to develop an alternative acquisition strategy, "spiral development," to field a limited near-term contingency system and develop incremental system upgrades to deliver the full Block I capability. APL has continued to support the NTW MPO through the various systems engineering activities needed to further define system concepts and approaches for the alternative acquisition strategy. These include refining the SRD, reviewing the contingency system design alternatives and assessing their performance, and developing the necessary design verification tools. While work is continuing on the NTW Block I contingency system, the NTW MPM is developing program plans for NTW Block II. In response to this, APL is putting in place the technical leadership, subject matter expertise, and analytical tools necessary to carry out the MTDA responsibilities for the NTW Block II Program. In close coordination with the MPO systems engineering staff, APL is assisting in the development of the organizational structure and the engineering plans and processes that will be needed to support the program definition and subsequent requirements analysis and system concept definition for Block II system acquisition.

System Performance Assessment

One of the unique strengths of the combined expertise at APL is the breadth of modeling, simulation, and analysis (MS&A) tools available to carry out the necessary analyses. Capabilities range from physics-based engineering design and phenomenology models to detailed, high-fidelity simulations of system elements. Throughout the concept exploration, design, and development phases of the program, representation of system functionality at varying levels of engineering complexity is needed. The APL MS&A tool set encompasses component-level high-fidelity models, system-level one-on-one battlespace models, and multisystem force-on-force campaign models. Applications include concept evaluation, design trade-offs, requirements feasibility assessment, algorithm testing, design verification, performance evaluation, T&E mission planning, etc.

The cornerstones of APL's Navy TBMD high-fidelity simulation suite are the FirmTrack AN/SPY-1 detection and tracking simulation, the SM-2 Block IVA six-degree-of-freedom (6-DOF) simulation for Navy Area, and the ALI/SM-3 6-DOF for NTW. Early in both TBMD programs the MPMs recognized the benefit of high-fidelity end-to-end simulation to accurately model the system response to complex threats and environments. At the direction of the MPMs, APL is currently integrating its high-fidelity system element models in a distributed High Level Architecture framework to provide end-to-end system modeling capability. The integrated model—Area/Theater Engagement Missile Ship (ARTEMIS)—is being developed in two variants, ARTEMIS-A for Area TBMD, and ARTEMIS-T for NTW TBMD. These simulations will more accurately model the complex dynamic interactions between the AWS and the in-flight missile, improving the realism of the digital representation of the weapon systems.

Detailed threat characterizations and an operational framework are necessary to bound the system analyses. APL's intelligence and threat engineering activities provide the Navy TBMD programs with the necessary insight into detailed TBM threat characteristics, tactics, and employment to support the formulation of system concepts as well as the TBM threat representations needed to assess the performance of those concepts. Threat characterizations include time-dependent and aspect-dependent signatures in the appropriate sensor wavebands (both IR and RF), flight events and timelines, physical attributes, and trajectories and body dynamics for all of the TBM stages, payload, associated debris, and chuffed propellant. For robust system design, these characterizations must account for statistical variations resulting from inherent design and production tolerances, atmospheric and environmental conditions, and uncertainties in the intelligence-based engineering description of the threat. Design Reference Missions (DRMs) are developed to furnish the development community with a set of consistent operational scenarios within which to evaluate high-level measures of system effectiveness. The DRMs provide detailed information on force laydowns, threat types, launch regions, defended assets, geographical constraints, and environmental factors affecting the employment of systems. Also described are potential adversary tactics including TBM raid sizes and how these may vary over the course of a conflict.

Area Preplanned Product Improvements

The Navy Area System, currently in engineering and manufacturing development, will provide U.S. and Allied forces and areas of vital national interest with an active defense against the TBM threat. While development continues, the Area Program is also performing systems engineering analyses to explore technology insertion into the baseline system to mitigate the stress factors induced by countermeasures as well as more advanced and continuously evolving TBM threats. An evolutionary approach to providing major performance improvements will offer an affordable capability that paces the threat while reducing schedule and technical risks. A Navy Area TBMD evolutionary program (Fig. 7) currently in the Definition Phase, could be based on incremental block upgrades, where the first step will provide enhanced capability against the program's objective threat. A Preplanned Product Improvement (P^3I) Working Group has been established by the MPO with participation of the PPOs and their Design Agents and Navy

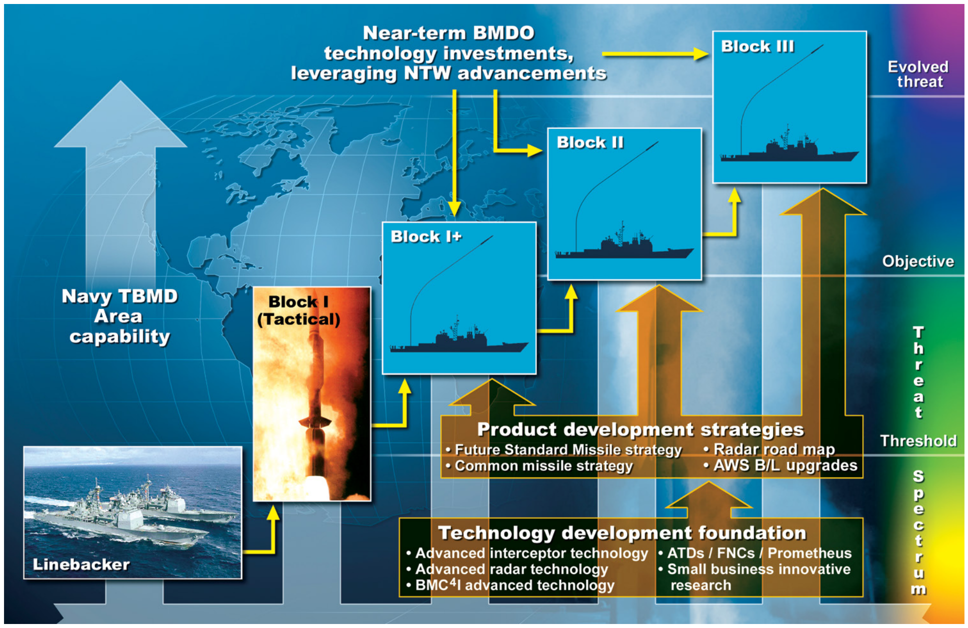


Figure 7. Notional evolution of the Navy Area TBMD System to pace the threat.

laboratories. The working group is examining baseline system performance capabilities and TBM threat characteristics, their evolution, and preponderance.

APL is undertaking a significant effort to conduct system performance assessments using high-fidelity digital simulations to accurately characterize the performance of the complex Navy Area TBMD System. Studies have used various methods to integrate the FirmTrack simulation results with the SM-2 Block IVA 6-DOF simulation (including Weapon Control System launch scheduling, midcourse guidance, handover, terminal guidance, and fuzing models). Recent analyses have added AN/SPY-1 radar coasting, primary object track switching, and target discrimination functions to FirmTrack. For the current Area P^{3}I analysis, the radar measurement errors calculated with FirmTrack are passed directly to the SM-2 Block IVA 6-DOF. Discrete data exchanges are still required between FirmTrack and the 6-DOF simulation, and modeling of the closed loop interactions between the AWS and the SM-2 Block IVA will be available when ARTEMIS-A is completed. This capability will support baseline system performance verification assessments to predict the overall probability of negation over the threshold as well as objective and extended defended areas so that expected system performance capabilities and limitations can be identified. These analyses will also support the development and "testing" of system design options for P^{3}I performance improvements against advanced and evolving TBM threats.

Having established the performance analysis methodology for the Area P^{3}I effort, the current focus of the APL activity is on the definition of suitable performance indicators to enable prediction of the impact of advanced threat stressing characteristics on AWS function/subfunction performance. These functions and subfunctions include the AN/SPY-1 radar and its associated signal processing, SM-2 Block IVA, and other elements of the AWS. APL is also assisting the MPM in identifying and leveraging technologies from related programs such as the NTW or BMDO science and technology programs to identify technology infusion opportunities and to help define the concepts for incremental block upgrades to the AWS. Performance analysis activities have already proven to be extremely useful in enabling identification of system improvements.

Test and Evaluation

The Area and NTW MPMs are responsible for the creation and execution of their respective Test and Evaluation Master Plan. APL provides technical leadership to both the Area and NTW TBMD MPOs in the detailed planning, execution, and analysis of system-level T&E activities. APL-designed test scenarios reflect test range safety and instrumentation limitations, operational realism, target definition and performance, and weapon system performance predictions. The realities of test range and ancillary sensor limitations due to cost, availability, safety, and other factors must be reflected in the designs. Weapon system performance predictions and target engageability analyses are generally performed to support test scenario design. APL combines the test requirements, target performance parameters, test range and ancillary instrumentation requirements, and safety and test event reconstruction requirements into mission requirements documentation.

For complex developmental and operational T&E events, TBM test targets must be specified, procured, tested, and fit into appropriate Area or NTW TBMD scenarios. These test targets must meet threat profile, radar cross-section, IR signature, and other criteria to ensure that the planned testing is realistic and will permit specification-level performance evaluation of the system. APL prepares the Target SRD and provides technical oversight of the test target design and development, focusing on compliance of the target configuration and predicted performance to the requirements necessary for the successful demonstration of Navy TBMD test objectives. The target vehicles are generally procured by the MPO through the BMDO Consolidated Theater Targets Program Office managed by the U.S. Army Space and Missile Defense Command.

The adequacy of the target emulation of specific threats is ultimately based on weapon system functionality and is assessed in detail as necessary to support the test target accreditation and certification processes. Once TBM targets have been specified and procured, the detailed knowledge of actual target performance is reflected in scenarios for testing the system. APL also provides specialized target instrumentation to assist in the post-test reconstruction of the events. At the execution level, APL assists the test conductor during rehearsals and flight test operations in activities such as calculating launch window restrictions and providing real-time assessment of target validity. In support of post-test evaluation, APL performs analyses of test target, off-board sensor, and weapon system data to support the overall assessment of flight test performance.

SUMMARY

The increasing examples of short- and medium-range ballistic missile proliferation worldwide underscore the importance of rapidly fielding an effective Naval TBMD capability, whether to support forcible entry into a theater by expeditionary forces or to provide a protective envelope over an entire theater of operations. The consistent implementation of disciplined systems engineering processes is key to the successful development of the complex systems that will form the foundation for the Navy Area and NTW capabilities in this critically important mission area.

The role of the Area and NTW MPMs cannot be understated; they are responsible for system development and deployment. In the final analysis this means assuring total systems engineering of the Area and NTW systems while maintaining a balance among cost, schedule, performance, and risk. APL supports both of these MPMs in ensuring that system design and performance meet the mission need and system requirements. Whether it is as a formal TDA, or simply as a trusted agent and technical advisor, APL acts as an "honest broker" on behalf of the MPMs in the identification and resolution of technical, performance, and system design issues stretching across the individual PPMs. By virtue of its mission and core competencies, the Laboratory is also at the forefront of the exploration of advanced and evolutionary Area and NTW system concepts.

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