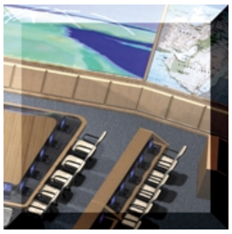

Theater Ballistic Missile Defense Analyses

Wayne J. Pavalko, Kanaya R. Chevli, and Michael F. Monius

The U.S. Department of Defense is funding the development of Army, Navy, and Air Force systems to defend against Theater Ballistic Missiles (TBMs) as part of a Joint Theater Ballistic Missile Defense (TBMD) architecture. The performance of these systems against TBMs is being assessed in operationally realistic situations throughout all phases of development. This article describes a portion of APL's role in the analysis of Navy and TBMD systems over the past several years. The results of the Laboratory's efforts have added to our understanding of the operational requirements and performance of these emerging TBMD systems. (Keywords: EADSIM, Modeling, Navy, Simulations, TBMD.)

BACKGROUND

Since the early 1990s, DoD has funded the development of Army, Navy, and Air Force systems to defend against Theater Ballistic Missiles (TBMs). Several APL departments have been an integral part of the engineering team analyzing the Navy's Theater Ballistic Missile Defense (TBMD) systems currently under development. Over the past several years, the Joint Mission Analysis Group (JMA) of the Laboratory's Joint Warfare Analysis Department has provided force-level and operational analysis of these emerging TBMD systems.

TBMs are guided rockets with conventional warheads or weapons of mass destruction that are launched at the enemy from long range. The German V-2 rockets that terrorized Londoners during World War II were the earliest examples. More recently, however, Iraq fired Scud missiles at Iran during the Iran/Iraq war, and at Israel and Saudi Arabia during Operation Desert Storm. The impact of a single Scud missile into the U.S. Army barracks in Dhahran, Saudi Arabia, caused the largest loss of life of coalition forces. The relative inaccuracy of most TBMs renders them ineffective for attacking specific military targets. However, their use as weapons of terror against cities and as vehicles for delivering weapons of mass destruction makes defense against them a high priority for the U.S. military.

TBMs typically have two phases of flight: boost and postboost. In the boost phase, the TBM is powered by burning solid or liquid fuel. The TBM guidance system maintains a trajectory so that the warhead will hit the desired location. After the fuel is depleted, the TBM transitions to the unpowered postboost phase, during which it flies ballistically (under the influence of gravity alone) toward the target. With some types of TBMs, the portion containing the warhead splits and flies separately toward the target. In this case, the warhead portion is called the reentry vehicle. The portion of flight before apogee or maximum altitude is the ascent phase, and the portion after apogee is the descent phase. Reentry starts when the TBM experiences significant effects of aerodynamic drag caused by the Earth's atmosphere. Some TBMs correct for guidance errors by modifying the trajectory of reentry during flight. Other TBMs, mainly short-range missiles, guide themselves to the target after reentry by homing in on radar signals emitted by the intended target. Figure 1 shows a typical TBM trajectory and the phases of flight.

All TBMD systems must perform three main functions: detection and tracking, threat assessment and engagement scheduling, and engagement. Detection and tracking involves creating a track or position estimate of the TBM via RF or IR sensors. Threat assessment and engagement scheduling entails analyzing the characteristics of a track to determine if it represents a threat and, if so, scheduling an engagement of the threat and managing the resources needed to support the engagement. In the final function, the TBM is engaged to prevent it from completing its intended mission (also called threat negation).

Surveillance systems assist TBMD systems in the detection and tracking function. These systems may be surface-based, airborne, or spaceborne. They contribute to Joint TBMD by providing early warning of TBM launches and, in some cases, estimates of the positions of the TBMs. Data from these surveillance systems are forwarded to TBMD units in the field to assist in performing the TBMD mission. The following subsections describe various ways in which the performance of Navy TBMD systems are analyzed.

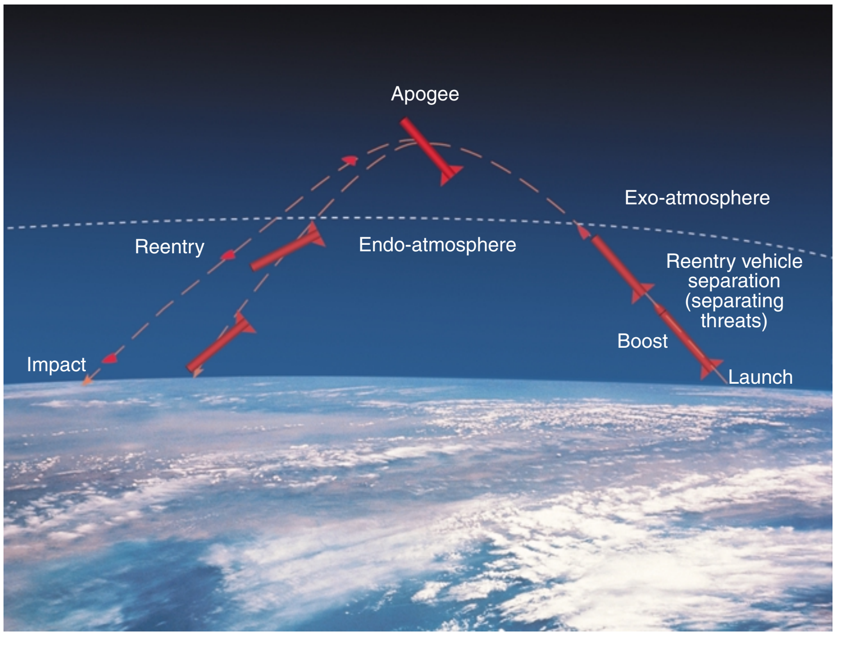

Figure 1. TBM trajectory.

One-on-One Analysis

One-on-one analysis assesses the performance of a single shipboard TBMD system against one TBM for a specific launch, impact, and ship geometry. This assessment can be done at a high or low level of detail, depending on the intended use of results. A high-detail assessment requires six-degree-of-freedom (6-DoF) threat models that generate position and body orientation information for the TBM's components during flight. IR and radar RF signatures of the TBM's components must be available for this kind of analysis. Detection and tracking of the threat is modeled via detailed simulations of sensors and the specific search doctrine used. The threat assessment and engagement scheduling function must be represented sufficiently to allow engagement of a single TBM. The missile portion of the engagement function is represented using 3- or 6-DoF engineering models. To determine whether an engagement results in negation of the threat, the type of TBM warhead and the expected damage to the warhead must be considered. Expected damage is assessed using detailed models of the impact of the defending missile and the TBM warhead for hit-to-kill systems or, in the case of blast fragmentation systems, impact of fragments on the TBM warhead.

Again, the result of one-on-one analysis demonstrates the performance of the system against a single TBM. When one-on-one analysis is run in Monte Carlo fashion, performance is given as a probability of threat negation. If the results for a fixed TBMD ship position and multiple TBM launch and impact locations are overlaid, the resulting display of defendable points is known as a defended area. If the results for multiple ship positions for fixed launch and impact locations are overlaid, the resulting area for which a ship can successfully engage the TBM is called an operating area. In general, defended areas display the region on the ground that can be defended from a threat launch region for a fixed TBMD system position. Similarly, operating areas display the region in which a TBMD system can operate or maneuver and still protect a region on the ground from a threat launch region. Figure 2 displays examples of defended and operating areas.

The results are also used to characterize the performance of a TBMD system concept and can influence the design of future systems. An example of one-on-one

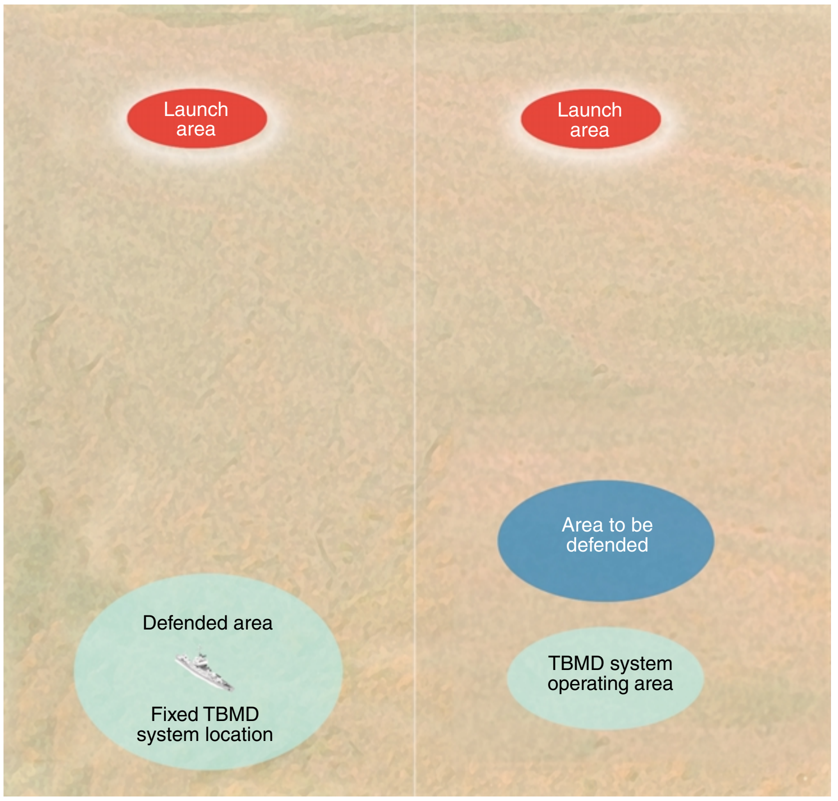

Figure 2. TBMD defended and operating areas.

analysis is the determination of the maximum three-dimensional engagement volume of a defending missile and the resulting defended area of the system. The combat system's engagement scheduling function uses this information to determine which threats can be engaged with a high probability of negation. When system performance is characterized in a simple way, e.g., using a defended area, the characterization is often employed in operational planning.

Many-on-One Analysis

Many-on-one analysis determines the effects of multiple targets that are closely spaced in time and space on all aspects of the TBMD system. The description of a TBM raid is usually in terms of *x* TBMs launching or impacting within *y* seconds. The simplest case is when TBMs impact the same location from the same launch point; the more complicated cases occur when TBMs hit a defended region from a threat launch region. Unlike engaging a single threat, engaging a raid may result in

- Reduction in the performance of sensors to detect and track each member of a group of closely spaced targets
- Degradation of defending missile performance when engaging a group of closely spaced targets
- The need for the combat system to schedule multiple, nearly simultaneous engagements

A detailed many-on-one analysis often uses the same tools as a detailed one-on-one analysis, with the addition of better engagement scheduling functions that account for multiple targets and the inclusion of multiple targets in the sensor models and 6-DoF missile models. The increased complexity of the many-on-one analysis also makes the presentation of results more difficult than the one-on-one analysis. Many-on-one analysis is usually presented for a specific threat raid and the system geometry based on the specific system's requirement documents. Results can be presented for a single raid size but are more often presented for a spectrum of raid sizes and timings.

Typical measures of effectiveness (MOEs) for many-on-one analysis are average number of targets negated, distribution of the number of targets negated, probability of negating all targets, average number of targets not negated, average number of targets unengaged, total inventory expended, and inventory expended per target. To compute these averages, many-on-one cases are typically run in Monte Carlo fashion, with enough iterations to reduce uncertainty in the outcome to an acceptable level.

The results of many-on-one analysis are also used to characterize the performance of a system concept and to influence the design of a future combat system. An example of many-on-one analysis is determination of the maximum number of engagements that can be processed simultaneously. The combat system may use this number during engagement scheduling to ensure that resources are available for all future engagements. When system performance in a multiple threat environment can be characterized simply, the characterization is often used to perform the many-on-many analysis described next.

Force-on-Force Analysis

Many-on-many or force-on-force analysis considers multiple TBMD systems against multiple threats. The complexity and scope of the problem increase significantly in force-on-force analysis because of interactions among defensive systems. Simple cases are analyzed using the detailed methods described for one-on-one and many-on-one analyses; however, complex cases typically require less detailed system models to reduce the time required for analysis. Although in one-on-one analysis the defending missile is modeled using a 3- or 6-DoF model, force-on-force analysis typically uses an approximation from time-of-flight tables, which specify the time required for a defending missile to fly to a point in space. Probability of single-shot engagement kill (P_{SSEK}) tables are used to represent the geometric dependency of the defending missile's performance.

Detection and tracking performance is also simplified for force-on-force analysis by taking results from higher-detail radar models and scaling detection ranges based on standard equations for radar propagation. The current force-on-force analysis approach used in JMA does not model radar resources or the dynamic reallocation of radar resources. Instead, the performance of TBMD systems is represented by limiting the radar resources for search and detection. Future analysis may require that limited radar resources and dynamic radar resource allocation be modeled explicitly.

The interaction among multiple TBMD systems is where force-on-force analysis differs most from the one-on-one and many-on-one analyses described earlier. These systems interact through specific communications paths such as data links among TBMD and surveillance systems that provide launch warnings and position estimates for TBMs (cues), data links among various TBMD systems (e.g., Link 11, Link 16, Cooperative Engagement Capability), and voice links among TBMD systems. Links to surveillance systems provide cues that may allow earlier detection of TBMs by TBMD systems if the cues are precise enough for local sensors to acquire the target. Links among the various TBMD systems also provide cues that may allow earlier detection. In cases where initial detection would be made too late or not at all by a ship's own system sensors, cues can substantially increase a system's performance. These links also facilitate engagement coordination among the TBMD systems. Coordination can range from simply notifying other units that a track has been engaged to exchanging detailed engagement information to support complex engagement coordination. (Voice links can also be used to exchange general operational information, but are not envisioned as the primary method to coordinate TBM engagements.)

The addition of other units in the analysis requires representing their systems, links among systems, and methods by which the units use the linked data. If the other units are TBMD systems, they are represented similarly as in one-on-one and many-on-one analyses. If they are strictly surveillance units, their sensor performance must be considered. In some cases, surveillance units are represented explicitly by modeling the RF or IR detection process of their sensors. In other cases, they are represented by assuming detection ranges and average delay times for receipt of the data by other units. The representations for links among systems vary from instantaneous communications to constant delays to detailed link modeling that includes throughput limitations. The way units use link data can also vary greatly. In the case of cues, the search process can be modeled explicitly or represented simply by assuming that cues are either not used by the receiving unit or that cues result in acquisition of the threat by the receiving unit after some time delay. The use of engagement coordination data varies greatly as well.

The simplest form of force-on-force analysis extends one-on-one or many-on-one by adding surveillance units that provide surveillance information. The results of this analysis show the effects of surveillance assets on one-on-one and many-on-one MOEs. These results are given as a function of relative positions of surveillance units and TBMD systems.

A more complex form of force-on-force analysis adds multiple engaging units and either single or multiple threats. This analysis is utilized to assess force-level performance and engagement coordination methods using multiple, identical systems or multiple systems of different types. For single threats, this approach shows the performance of multiple units against a single threat. For multiple threats, it shows the performance of multiple units against multiple threats and is used to evaluate multi-unit raid rate requirements and engagement coordination concepts. In addition to many-on-one MOEs, other measures are computed to determine the efficiency of engagement coordination methods.

A primary tool for force-on-force analysis at APL is the Extended Air Defense Simulation (EADSIM), which was developed by Teledyne Brown Engineering for the Ballistic Missile Defense Organization (BMDO). APL has employed EADSIM since 1992 and is now one of its main users within the Navy. JMA has developed methods to input 3- and 6-DoF data into EADSIM and maintains an extensive database of performance data for use in TBMD analyses. EADSIM provides generic system representations that can be tailored via input data to model several TBMD systems.

Operational Analysis

Operational analysis applies one-on-one, many-on-one, and force-on-force analyses to operationally realistic situations. It involves examining specific TBM trajectories and specific unit locations that are tied to geographic areas. Operational analysis usually does not require major changes in analysis methodologies. However, the rotation of the Earth can affect the trajectories of long- and medium-range TBMs. In addition, the terrain blocking the line of sight between sensor and threat can affect the detection performance of

TBMs. These problems are amplified when considering low-altitude airborne targets. For some systems, the presence of rain or clouds in an operational situation can greatly influence system performance.

Several sources of data in the DoD community describe potential operational situations where TBMD systems may be deployed. For example, BMDO publishes operational scenarios that describe campaigns and specific operational situations. For some Navy TBMD systems, Design Reference Missions (DRMs) are used for analysis. These DRMs are typically tailored to the acquisition community and stress specific system requirements. Both BMDO and DRM products provide descriptions of the operational situation, friendly assets that require defense, friendly forces available in theater, and hostile forces and their attacks on friendly assets and forces.

One-on-one analysis results are often used to determine TBMD system performance in operational situations. In the simplest example, defended or operating areas are overlaid on a map of the region corresponding to the operational situation. In some cases, performance that appears significant in one-on-one or many-on-one analysis can be less significant when considered operationally. An example is a large ship operating area that is mostly over land, or as shown in Fig. 3, a large defended area that contains only a portion over land.

Force-on-force analysis is the primary user of operational situations. Many examples of TBMD force-on-force operational analysis exist. The BMDO Capstone Cost and Operational Effectiveness Analyses (COEA) Phases I and II and the Navy TBMD COEAs Phases I and II both made significant use of force-on-force operational analysis. APL participated in Navy TBMD COEAs by providing one-on-one, many-on-one, and force-on-force operational analysis support. BMDO and the Joint Theater and Missile Defense communities continue to perform operational analyses of Joint TBMD systems.

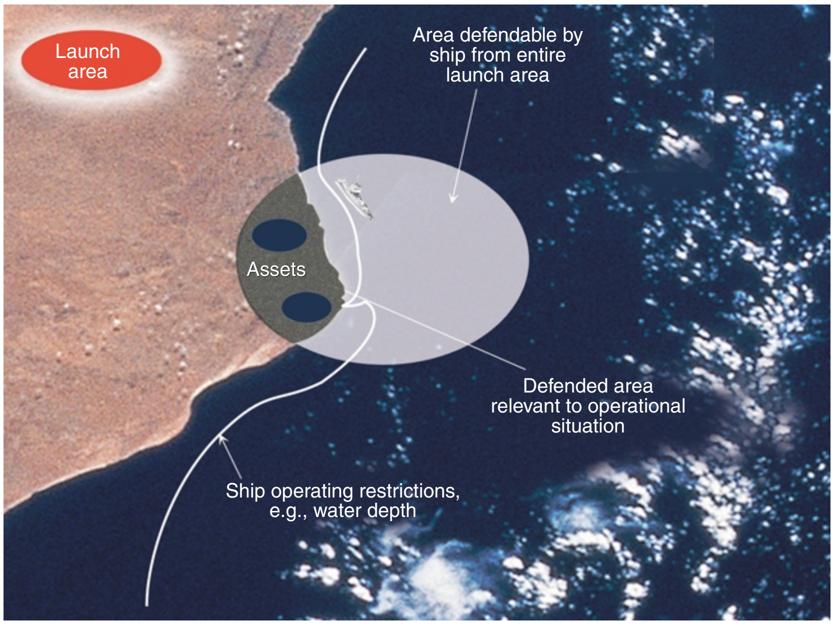

Figure 3. One-on-one defended areas applied to an operational situation.

APL's ROLE IN TBMD ANALYSIS

The following discussion describes specific TBMD analyses performed by APL to support the development and interoperability of Navy and Joint TBMD systems.

Navy Area Defense Operational Analysis

The Navy Area Defense (NAD) TBMD system is designed to defend inland and coastal assets from TBMs. One requirement of the system is to defend a specified distance inland from the coast. To evaluate the inland coverage of the NAD system, the results of one-on-one and NAD system performance data were input into EADSIM. Of primary interest here was determining which inland assets in each of several operational situations could potentially be defended by a NAD system. Since the extent of the defended area depends on the direction and range of the threat, threats from multiple azimuths and ranges were considered. The analysis included the water depth operating restrictions of NAD ships, which affect their placement. In many areas, especially those away from ports and channels, water depth operating restrictions require a ship to remain some distance from the coastline. To determine if an inland asset was defendable from a specific threat azimuth, the asset was targeted by a TBM from that azimuth. EADSIM, using a representation of threats that the NAD system could engage, determined if a ship in any of the allowable ship positions could defend that asset.

The result of this analysis yielded an estimate of potential inland coverage of the NAD system and indicated which assets might be defendable by the NAD system from different threat azimuths. These results can be used to evaluate the NAD inland coverage performance relative to requirements and to help planners determine the allocation of TBMD systems (e.g., see Fig. 4).

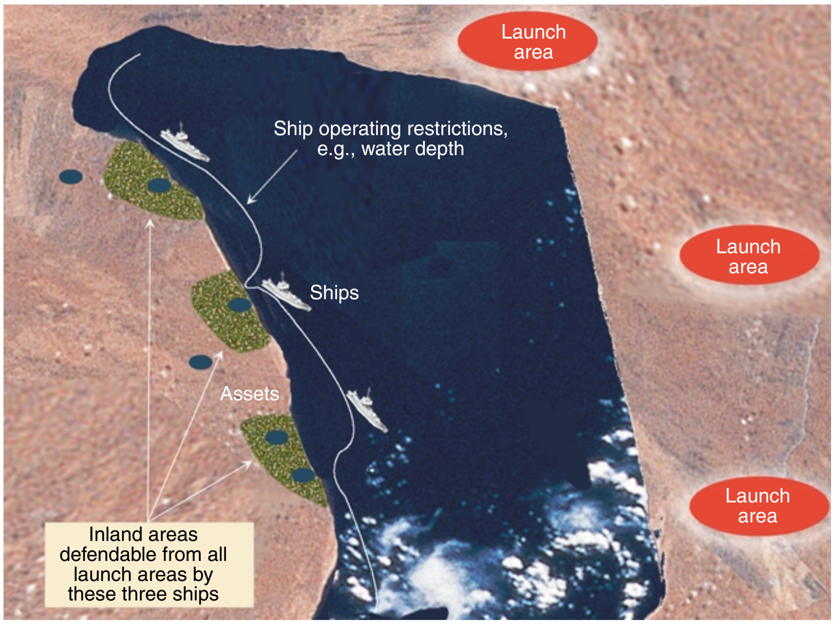

Figure 4. Notional inland coverage of a Navy Air Defense TBMD system.

Joint Force-on-Force Analysis

APL has participated in the analysis of NAD and Patriot PAC-3 interoperability. Both systems will be deployed early in this decade; their defensive capabilities may have overlapping TBMD coverage. Not surprisingly, interoperability between NAD and Patriot units is of significant interest.

JMA analyzed the capabilities of NAD and Patriot systems in situations where their TBMD coverage overlapped. Their representations in EADSIM were used to generate Joint defended areas. The analysis was performed with and without coordination between the two systems. The results quantified the individual and Joint capability of the PAC-3 system with a NAD system operating in several locations relative to the PAC-3 firing unit. In addition, detection and launch times of each unit were determined, and these data assisted in the analysis of Joint engagement coordination methodologies.

Navy Theater-Wide Operational Analysis

Although most one-on-one analyses are performed for single threats to generate defended or operating areas, single threat operating areas can be combined to generate operating areas for multiple threats. In support of Navy Theater-Wide (NTW) analysis, JMA used EADSIM and system performance data from the APL Air Defense Systems Department to represent the NTW Block I system. Several DRM operational situations were analyzed, and the operating areas for multiple threats were computed by using a large grid of ship positions and determining the number of threats that could be defended against from each position.

This analysis methodology was also applied to more general launch regions and defended regions as opposed to operational situations. In this case, threats could be launched from anywhere inside a defined launch region and hit anywhere inside a defined defended region. A grid of ship positions was used to determine the operating areas from which an NTW ship could defend the entire defended region against such threats. The results showed the operational capabilities of the NTW Block I system design and can be used to compare operational areas for multiple system concepts. Notional results from the NTW Block I operating area analysis are shown in Fig. 5. The shaded region is the operating area in which an NTW Block I ship can operate and defend all inland assets

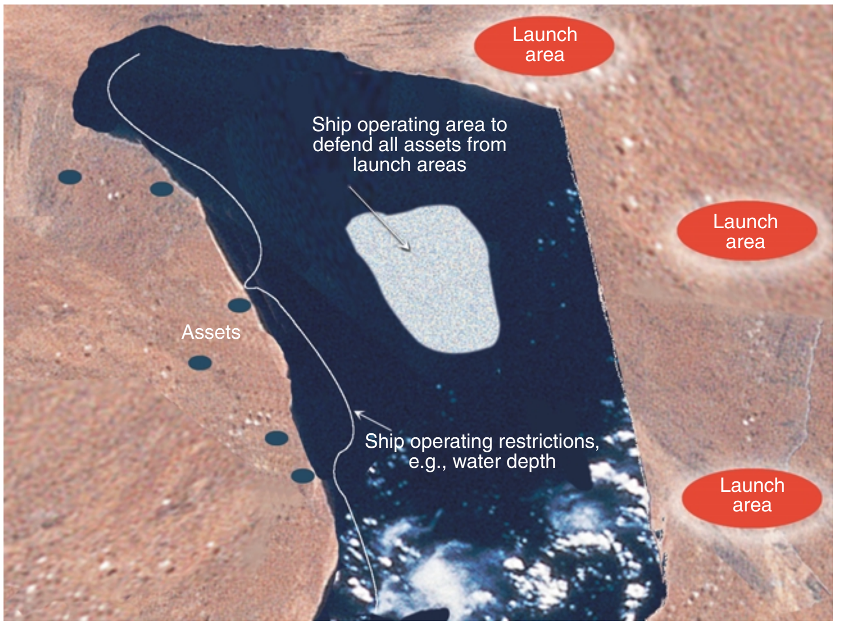

Figure 5. Notional NTW operating area.

from all three launch areas. Normally, more inland assets or more launch areas will decrease the effective operating area of the system.

APL also played a key part in producing the System Requirements Document (SRD) for the NTW Block I system. For example, one area of investigation was the Battle Management Command, Control, Communications, Computers, and Intelligence (BMC^4I) engagement coordination trade study. The goal here was to determine BMC^4I requirements for the NTW Block I SRD. JMA participated in the study by analyzing engagement coordination options in an NTW DRM operational situation.

The NTW Block I system was represented in EADSIM as was the operational situation employed in the analysis. A simplified communications link model that assumed constant message delay times was used. Sensitivity analysis on the delay time was performed to determine the effects on the performance of multiple systems. Engagement coordination options considered were (1) no coordination, and (2) two proposed coordination options (coordination Methods A and B in Fig. 6b). Each option used the engagement coordination method in EADSIM, which provides only an approximation to the actual candidate options. Each option was run with at least six different message delay times and six different values of an important combat system parameter, i.e., the maximum number of targets engageable simultaneously by a ship. Scenarios were run with 100 Monte Carlo iterations. The analysis included the ability of the platforms to accept link data and use cues to acquire targets earlier than each could using only ownship sensors. The results showed the benefits of coordinating engagements when TBMD resources were limited. A depiction of the type of operational situation and the notional results from the NTW Block I engagement coordination analysis are shown in Fig. 6. The results showed that performance increases as each ship can engage more targets simultaneously. In addition, either of the two proposed types of coordination provided significant increases in performance over the no coordination option. This increase occurs because when a single ship has a limited number of simultaneous engagements, over-engagement of targets by one or more ships may result in unengaged targets.

CONCLUSION

Analysis of TBMD systems at APL is supporting the development of a Joint TBMD architecture that will provide robust and effective protection against TBMs into the future. The Joint Warfare Analysis Department contributes to Navy and Joint TBMD efforts with operational analyses of current and emerging Joint TBMD systems. There are many challenges ahead in Joint TBMD, especially in the area of interoperability. Force-on-force operational analysis will continue to play a major part in defining the requirements and evaluating the operational performance of these Joint systems.

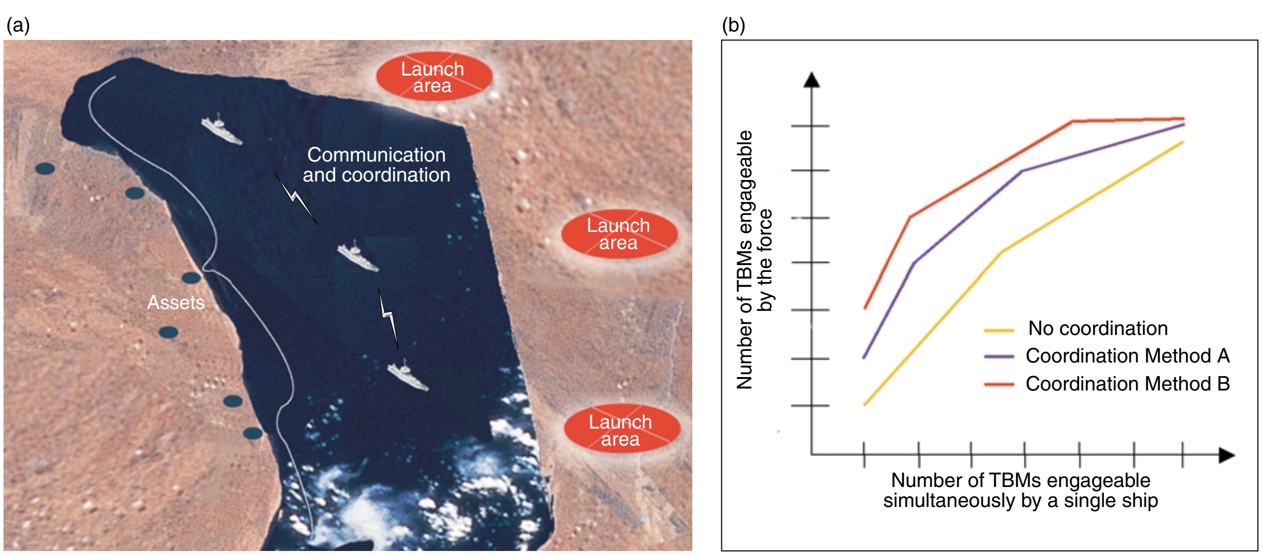

Figure 6. The NTW Block I engagement coordination analysis: (a) simplified scenario and (b) notional results.

THE AUTHORS

WAYNE J. PAVALKO received B.A. and M.S. degrees in mathematics from Hiram College in 1991 and Purdue University in 1993, respectively. Since joining APL in 1994, he has been an analyst in the Joint Mission Analysis Group of the Joint Warfare Analysis Department. Mr. Pavalko has expertise in Navy TBMD force-on-force and operational analysis as well as modeling and simulation. In addition to working at APL, he is also a part-time instructor in mathematics at Howard Community College. He is a member of the Military Operations Research Society. His e-mail address is wayne.pavalko@jhuapl.edu.

KANAYA R. CHEVLI received a B.S. degree in mathematics with a second major in physics from the University of North Texas in 1992 and an M.S. degree in physics from the University of Alabama at Huntsville in 1995. He worked as an Operations Research Analyst at the U.S. Army Missile Command until 1997 and then joined APL as an analyst in the Joint Mission Analysis Group of the Joint Warfare Analysis Department. Mr. Chevli has expertise in Navy TBMD analysis and modeling and simulation. He is a member of the Military Operations Research Society. His e-mail address is kanaya.chevli@jhuapl.edu.

MICHAEL F. MONIUS earned a B.S. degree in mathematical sciences from Loyola College of Maryland in 1995 and an M.S.E. degree in mathematical sciences from The Johns Hopkins University in 1997. His principal areas of study were discrete mathematics and algorithm design and analysis. He joined the Joint Mission Analysis Group of the Joint Warfare Analysis Department in June 1997, where he is now an analyst. Mr. Monius has expertise in TBMD modeling and simulation, and operational analysis and force effectiveness. His e-mail address is michael.monius@jhuapl.edu.