RODNEY P. REMPT and MARVIN J. LANGSTON

THEATER MISSILE DEFENSE: TECHNOLOGIES TO SUPPORT A NEW NAVAL MISSION

The increased global threat of tactical ballistic missiles has revitalized a national program for joint theater missile defense since the Persian Gulf War. A critical element of this new defense capability will be a sea-based component consisting initially of a relatively short-range system based on a modified Standard Missile and associated changes to the Aegis combat system. A sea-based theater-wide capability may be introduced to complement the land-based Theater High Altitude Area Defense system under development. The Ballistic Missile Defense Organization (formerly known as the Strategic Defense Initiative Organization) and the U.S. Navy are investigating the options for this capability. This article discusses the technologies and system concepts under consideration for the sea-based theater missile defense component.

INTRODUCTION

The televised explosions of Patriot missile warheads defending Saudi Arabia and Israel against the Iraqi-launched Scud ballistic missiles vividly demonstrated the need for a more effective defense against short- and medium-range ballistic missiles. This class of weapons is now held by twenty-eight countries, and many of them are potentially hostile to U.S. interests. Within minutes after launch, these weapons can deliver conventional high-explosive warheads or mass destruction warheads (chemical, biological, or nuclear) at ranges from 80 to 3000 km (for a comprehensive report on ballistic missiles, see Ref. 1).

President Bush recognized the pervasive spread of these relatively inexpensive but terror-inducing weapons in his State of the Union address in January 1991:

> I have directed that the SDI [Strategic Defense Initiative] program be refocused on providing protection from limited ballistic strikes, whatever their source. Let us pursue an SDI program that can deal with any future threat to the United States, to our Forces overseas and to our Friends and Allies.

The Congress affirmed this call in the 1991 Missile Defense Act, which calls for

> the development of deployable and rapidly relocatable advanced theater missile defenses capable of defending forward-deployed expeditionary United States Forces . . . by the mid-1990s.

Given the regional instabilities that have arisen since the collapse of the Soviet Union and the rapid global growth of ballistic missile weapons, the 1991 Missile Defense Act makes eminent sense if the United States is to protect its interests and foster peace throughout the world. As Figure 1 shows, the threat from tactical ballistic missiles (TBM's) is real and growing, both in numbers of weapons and in the political and military effects of their use. Analysts project that as many as forty-one countries will acquire or produce this class of weapons by the year 2010.

At the same time that TBM's are proliferating, they are becoming more accurate. As inexpensive homing and inertial reference systems (e.g., the Global Positioning System) become widely available during this decade, TBM accuracies are expected to improve dramatically. The National Security Industrial Association (NSIA) reports that the inertial accuracy

> has been variable, as poor as 10 mils [one mil equals one thousandth of a radian or approximately 0.057°] exhibited in the Persian Gulf by 1970s Soviet technology Scuds, to projections of 0.1 mil [which translates to] (50 m at 500 km) for future systems.[2]

Although U.S. defense specialists consider these weapons to be tactical, to distinguish them from the 3000-km or greater range of intercontinental ballistic weapons, small countries favor them because they represent a strategic capability against regional neighbors. Such highly mobile truck-launched weapons, furthermore, can be operated with a small military infrastructure and deliver ordnance that is very difficult for air defenses to neutralize. The NSIA makes the point that the

> infrastructure required to prepare and launch TBM's is orders of magnitude less costly than the airports, aircraft carriers, and other facilities needed to support the aircraft commonly used to deliver offensive ordnance. Also, the relative simplicity of missiles and support equipment is responsible for the ease with which TBM's can be moved and hidden. Further, training of personnel to operate and maintain TBM's is far simpler than that with aircraft.[2]

Thus, the potential threat missiles are increasing in numbers and improving in range and accuracy. The sit-

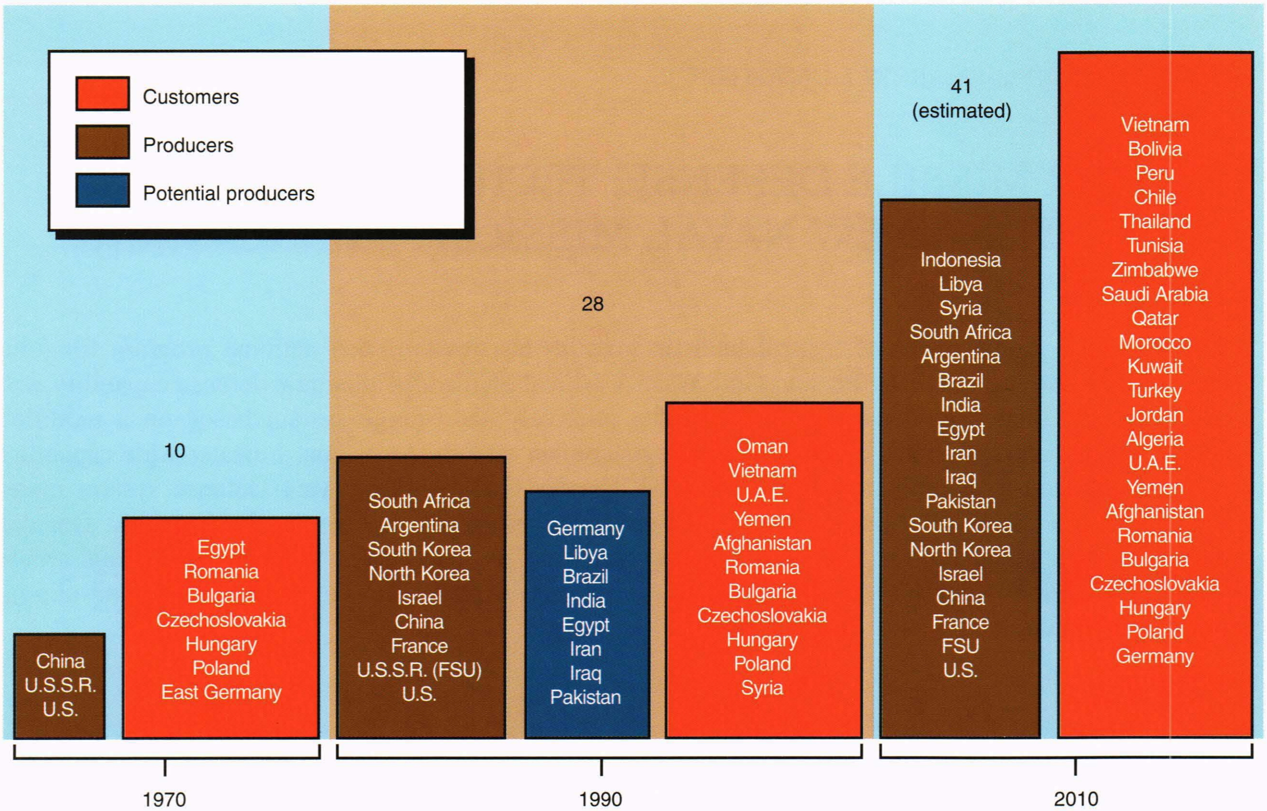

Figure 1. Actual and expected growth of tactical ballistic missile producer and customer countries (FSU = Former Soviet Union).

uation will become ever more disruptive to our political and military interests unless the United States can mitigate such threats. Countering the threat will require a multifaceted and multitiered response, including, in most plausible scenarios, the contribution of both land- and sea-based air defense assets.

DEFINING A THEATER MISSILE DEFENSE PROGRAM

In response to congressional direction, the DoD and the Ballistic Missile Defense Organization (BMDO) initiated the Theater Missile Defense (TMD) program. The Joint Chiefs of Staff Require Operational Capability (JROC) Mission Need Statement (MNS) for TMD defines the following four architectural elements:

1. Attack Operations: Offensive operations to prevent enemy missiles from being launched by destroying launch platforms, support facilities, command and control complexes, and missile stocks.
2. Battle Management/Command, Control, Communications, and Intelligence (BM/C3I): Facilities and supporting infrastructure to provide early warning and coordinated operations throughout the theater of operations.
3. Active Defense: Defensive operations to destroy incoming ballistic weapons as early as possible to prevent warhead impact or collateral damage from falling debris.
4. Passive Defense: Any means that can reduce the damage from incoming weapons, including warning, camouflage, deception, dispersal, mobility, redundancy, and personnel protection.

Since each pillar of TMD is critical, the BMDO, with the services, is developing the active defense and the portion of BM/C3I that relates to active defense.

A NEW NAVAL MISSION

As in other national security missions, naval forces can provide ballistic missile protection before, during, and after the deployment of ground-based theater forces into a regional conflict zone. Forward-deployed U.S. Navy ships operating from the 12-mile limit of international waters provide the presence and mobility that can uniquely support theater ballistic missile defense (TBMD) in many locations and crisis scenarios.

Such sea-based ballistic missile defenses will be an integral part of the ongoing BMDO TMD program, which includes improvements to the U.S. Army's Patriot air defense system, the acquisition of the Theater High Altitude Area Defense/Ground-Based Radar (THAAD/GBR) system, improved processing and distribution of the U.S. Air Force's early warning satellite information to cue defense systems, and improvements to the theater-wide real-time command and control systems. Aegis cruisers and destroyers will be modified to provide an initial area defense of debarkation ports, coastal airfields, amphibious objective areas, and land-based expeditionary forces. This preliminary naval capability may be augmented with a theater-wide defense of joint forces, cities, vital assets, and inland regions within the entire operating region. With 100 km of sea-based overland TBMD coverage, 60% of the world's population centers can be protected—

a compelling rationale for assigning this mission to the maritime forces.

THE PROBLEM OF BALLISTIC MISSILE DEFENSE

Although ballistic weapons can be purchased or manufactured and then deployed by developing nations with relatively small defense outlays, defending against such weapons is extremely difficult and costly. Ballistic weapons can deliver destructive force across hundreds of kilometers within minutes from launch (e.g., a ballistic missile with a 500-km reach flies for about six minutes from launch to impact). They present, moreover, an inherently small target to defensive systems and fall on their intended targets at speeds ranging from 1 to 4 km/s.

Launch determination is usually made by space-based infrared (IR) sensors that cannot detect the ascending missile until it rises above any clouds over the launch point. After the missile passes through the cloud layer, it has only seconds of rocket burn time remaining (when it is most easily detected) before it begins its unpowered ballistic path up through trajectory apogee and then back down to its intended target. As the missile begins to descend, it can tax the defensive weapon system by deploying decoys, breaking up spent rocket stages, or maneuvering to avoid interception and destruction.

The relatively small size and uncluttered design of these missiles give them an inherently small radar cross section. Further reductions are possible using available low-observable technologies. In the IR spectrum, TBM's have an enormous signature during the rocket boost phase (nominally only the first sixty seconds of flight); however, throughout the remainder of the flight, the relatively cool missile body further cools in the exoatmosphere until it begins to reheat following reentry into the atmosphere.

The short flight time and high descent speed of TBM's make it difficult to achieve a high kill probability with a single defending missile. Unfortunately, all of the advantage goes to the offense. The offenders are free to choose when to attack, how to attack, and where to attack, whereas the defenders are forced to be prepared for action at any time and any place. This situation causes air defense systems to be designed for the greatest number of engagement opportunities (i.e., to engage the incoming weapon as early as possible along its flight path and reengage it as often as time permits until it is destroyed). That objective can be achieved by delivering multiple shots with a single TBMD system or by creating more than one defense layer, each optimized for engagements in a portion of the battlespace.

DEFENDING THE THEATER OF OPERATIONS

The potential engagement sequence for sea-based TBMD is shown in Figure 2. When a space-based system, such as one deployed by the U.S. Air Force's Defense Support Program (DSP), detects a threat missile's rocket plume, the system will estimate the missile launch point and the trajectory of its flight path. This information will be fed within seconds via satellite communications links to the Aegis ship to cue (i.e., provide target location information) the Aegis AN/SPY-1 multifunction phased-array radar. The radar will then be scheduled to conduct a limited search until a firm track is established. On the basis of the target track and the interceptor flyout parameters, the Aegis weapon system will calculate the first engagement opportunity and launch a modified Aegis Standard missile or a long-range TBM interceptor. The Aegis weapon system will then look for a target destruction opportunity and reengage the target if necessary, time permitting. This same engagement sequence can be completed without space-based cueing, but, depending on the scenario, the available engagement time may be reduced because the normal continuous Aegis AN/SPY-1 volume search may detect the missile later in its flight. Airborne IR sensors are also candidates for early cueing, but such systems are not currently deployed.

The foregoing ballistic missile defense scenario is a significant change to naval antiair warfare. The current Aegis system is designed to engage aircraft or antiship cruise missiles attacking the battle group or amphibious forces. Those threats move at slower speeds (typically less than 1 km/s) and attack the battle group at ranges from 30 to 400 km. Ballistic missiles, in contrast, are faster, can be launched from longer ranges, and are generally aimed at land-based targets.

These conditions make it extremely difficult or impossible to develop a perfect single-service system to defend against ballistic missiles in the theater of operations. The history of air defense systems has shown that the only effective defense is a layered defense in which successive layers engage threat missiles as they approach the intended target. Applying such an air defense technique becomes more difficult in ballistic missile defense because of the short time available between the first shot opportunity and arrival of the weapon at the target. Thus, a fully successful ballistic missile defense for a theater of operations will probably require complementary sea, land, air, and space systems to support the full range of potential military scenarios. Those systems will include the following:

1. Early warning space and/or aircraft surveillance.
2. Both ground- and sea-based air defense systems.
3. A layered, multitier engagement capability.
4. Theater command and control components.
5. Various theater sensors (such as airborne IR search and track) to provide weapon battery cueing.

For each requirement, new or improved technologies will be needed to support the following:

1. Space-based IR sensors and communications systems.
2. Improved ground- and sea-based radar and missile control systems.
3. Airborne IR and radar sensor and fire control systems.
4. Improved missiles that can quickly deliver explosive warheads or hit-to-kill kinetic kill vehicles (KKV's) to targets in both endo- and exoatmospheric flight.

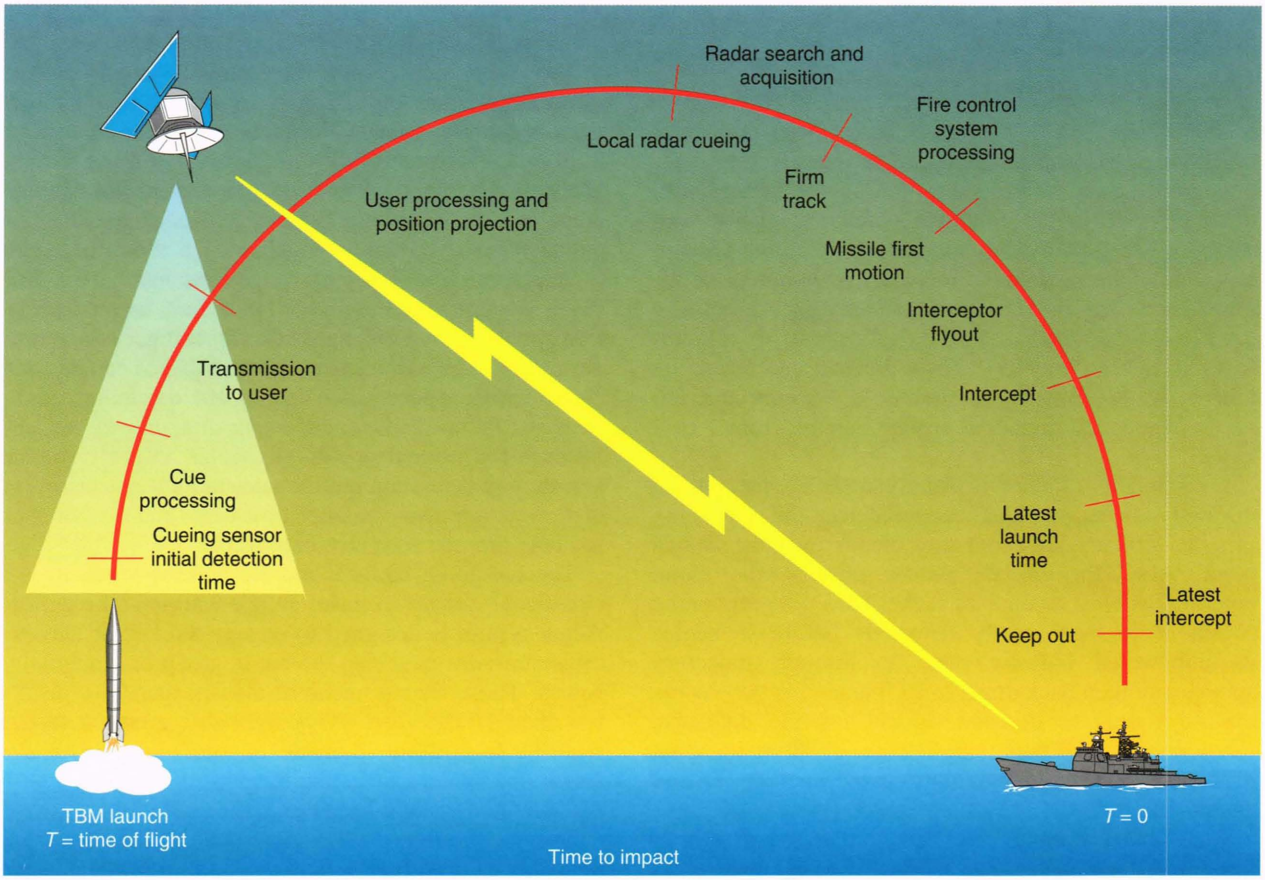

Figure 2. Potential engagement sequence for sea-based tactical ballistic missile (TBM) defense (T = time).

5. Navigation systems that allow engagements hundreds of kilometers from the defended area.

6. Command and control systems that facilitate accurate and efficient split-second decisions across the entire theater of operations.

AN ARCHITECTURE FOR TMD

In many respects, the development of TMD is an extension of the Patriot land-mobile air defense system and the sea-based Aegis multiwarfare weapon system. These systems, designed to detect, track, and engage enemy aircraft and missiles, have evolved to a high level of effectiveness over the past two decades. Although they are not functionally comparable, both employ computer-controlled phased-array radar technology and automated missile fire control elements that guide the defensive missiles to the target. Whereas Patriot is dedicated to the air defense of a threat sector, the Aegis weapon system is the heart of an integrated multimission (antiair warfare, antisurface warfare, and antisubmarine warfare) surface ship that maintains the total air picture over the full horizon to zenith for a 360° volume of the battlespace. (Displays being developed for future use in this combat system are shown on the inside of the back cover of this issue.)

In Operation Desert Storm, the Patriot system successfully defended against the Scud ballistic missiles, and the Aegis system demonstrated its ability to detect and track those same missiles. The TMD issue now is how to counter current and evolving threats in a cost-effective way. The primary emphasis is on driving the engagements out to earlier/higher intercept opportunities with improved offensive kill methods. Early encounters will help prevent debris from impacting defended areas and may allow additional engagement opportunities.

The large variation in threat-missile range (and therefore warhead reentry speed) and the variations in threat payloads (from unitary explosives to cluster munitions and mass destruction warheads) have led the U.S. Army to adopt an evolving two-tier (BMDO refers to a defense layer as a tier) architecture. A modified Patriot system will provide the near-term lower-tier capability, which may eventually be augmented or replaced by a new system technology under conceptual development in the U.S. Army Corps Surface-to-Air (CORPSAM) Missile System program. To provide for upper-tier defenses, the U.S. Army, in the fall of 1992, awarded to the Lockheed Missiles and Space Company and the Raytheon Company, respectively, a demonstration/validation contract for the development of the THAAD system and its associated GBR.

The U.S. Navy's sea-based TMD may also employ a two-tiered architecture. The Aegis weapon system's Standard Missile 2 Block IV (SM-2 Block IV) will be modified with a dual-mode IR/RF seeker, called SM-2 Block IVA, to improve its performance against short-range ballistic missiles. This lower-tier capability may provide the primary initial on-scene response for a theater Commander-in-Chief (CINC) faced with a TBM threat. With the addition of a sea-based upper tier, this initial capability will evolve to a much wider defense of joint forces, cities, vital assets, and inland regions within an entire theater of operations. The following sea-based upper-tier concepts are being considered:

1. The Light Exoatmospheric Projectile (LEAP) hit-to-kill KKV plus an Advanced Solid Axial Stage (ASAS) booster rocket integrated with the first two propulsion stages of the SM-2 Block IV missile.
2. A sea-based variant of the Army's THAAD missile.
3. Some combination of the two.

The scientific principles and technologies to create the necessary improvements to these systems have largely been demonstrated. Missile kinematic and guidance technology, radar and fire control technology, and command and control technology are all sufficiently understood to support this system engineering challenge. Technology studies, however, continue to address the following issues:

1. Hit-to-kill warheads versus blast fragment warhead lethality.
2. Architecture and system engineering trades between exoatmospheric and endoatmospheric missile engagement concepts.

The critical criterion for success is to be able to apply these enabling technologies in a way that will yield the desired system results.

KILL VEHICLE TECHNOLOGIES

During the past decade, the BMDO as well as the former SDIO has invested over $400 million in technologies to neutralize ballistic missiles or ballistic reentry vehicle warheads during the exoatmospheric portion of threat-missile flight. Eliminating threat warheads above the atmosphere will minimize inadvertent damage from warhead debris and permit pre-apogee intercepts before the deployment of decoys, multiple reentry vehicles, or other penetration aids.

The LEAP was originally funded by BMDO to develop a small hit-to-kill projectile launchable from an electromagnetic rail gun. As such, LEAP was developed to weigh less than 10 kg, to be robust enough to withstand extreme launch shock, and to be smart enough to locate and track a target within its field of view. This device has evolved away from the original rail gun constraints and is now a potential hit-to-kill KKV for a ship-, air-, or ground-launched tactical missile.

Current designs nominally include midwave or long-wave IR KKV seekers using 128- or 256-thousand-element focal-plane arrays. These sensors have a small field of view and a fixed aperture. To protect the IR seeker from atmospheric heating, it remains covered by a shroud until after the KKV has been separated from the final ASAS missile stage. The KKV uses a miniature interferometric fiber optic gyro to provide the divert and attitude control system accuracy needed to fly the KKV into the closing target during the last few seconds of the engagement. Target destruction results from the KKV's mass impacting the target at high closing speeds (nominally 2 km/s or greater). With this class of low-mass KKV, some form of kill enhancement mechanism may be required to ensure 100% lethality against threat warheads containing small canisters (submunitions) filled with lethal chemical or biological agents.

The KKV's exoatmospheric flight is controlled by either liquid hypergolic-fueled (i.e., fuels that ignite upon contact) divert and attitude-control motors or a solid rocket divert motor combined with a hot-gas attitude control system. Divert motors are the means by which high endo- or exoatmospheric space vehicles alter their ballistic or orbital flight path. The liquid technology allows divert pulses to be started and stopped as needed to produce smooth and accurate guidance, but it represents a possible toxic hazard aboard ship. Solid-fuel divert motor technology improves shipboard handling and safety, but once the rocket motor is ignited, it burns continuously until consumed, thus imposing tighter endgame timing constraints on the engagement. The LEAP exoatmospheric KKV's are designed to function slightly down into the atmosphere (below 100 km). Below these altitudes, aerodynamic drag and IR sensor heating prevent reliable intercepts with the current designs.

The Army's THAAD missile is being designed to engage TBM targets in both the high endo- and exoatmospheric regimes. The THAAD KKV uses an IR seeker and liquid-fuel divert and attitude-control motors (designed to operate for short periods in the high endoatmosphere) to complete hit-to-kill intercepts after separation from the THAAD single-stage solid rocket motor. This missile provides engageability similar to the LEAP concepts for long-range threats and greater engageability for shorter-range threats. The THAAD is also being studied as a candidate for the sea-based theater defense interceptor. If selected, it would be modified to launch from the Aegis Vertical Launching System (VLS) (the VLS launchers store the missiles in vertical canisters and launch them directly from the canisters). Preliminary findings indicate that the modifications needed to meet the VLS operational and safety requirements may result in only partial commonality of the sea-based THAAD missile with the land-based THAAD missile.

MISSILE TECHNOLOGIES

Current Aegis ship combat systems using the Aegis weapon system, the AN/SPY-1 multifunction phased-array radar, the SM-2 missiles, and the Mark 41 VLS provide highly capable battle force defenses against antiship cruise missiles. If ballistic missile defense capability is added, these Aegis ships will significantly improve the theater CINC's defensive effectiveness against ballistic missiles. By using the SM-2 Block IV missile as the baseline for a lower-tier system, TBMD will become an integral part of the Navy's Aegis air defense system.

The SM-2 Block IV missile uses a rapid-burn first-stage rocket motor plus a dual-burn (boost plus sustainer) second-stage rocket motor. If the LEAP KKV concept is selected as the upper-tier missile, the SM-2 Block IV will be augmented with a third-stage "kick" motor to accelerate the LEAP KKV into exoatmospheric position before the endgame intercept. This three-stage configuration will theoretically provide the theater CINC with TBM defensive coverage having a radius of several hundred kilometers against long-range threats. Similar theoretical coverage could be achieved using the sea-based THAAD option if the THAAD thrust-vector-controlled rocket motor and the endo/exoatmospheric KKV were coupled with the SM-2 Block IV first-stage booster motor.

EARLY WARNING SENSOR TECHNOLOGIES

As previously described, the long range and short flight time of ballistic weapons present a significant challenge to defensive systems. For the same reason that strategic defensive systems have incorporated the DSP as the early warning component of an integrated system, TBMD systems need similar early warning information.

The DSP geosynchronous satellite constellation uses a scanning IR telescope to monitor most of the Earth's surface continuously for ballistic missile launches. Information from the telescope is fed into the command and control network at the U.S. Space Command, Cheyenne Mountain, Colo., to alert the strategic forces. Minor modifications have been developed for the DSP so that it can provide equivalent capability for TBM launches. This preliminary information will be processed at Cheyenne Mountain or at theater processing centers and then passed as warning and cueing information for both ground- and sea-based TBMD systems. Because the Aegis multifunction radar will be searching for cruise missiles while tracking air and surface contacts within its battlespace, the DSP cue, possibly augmented with airborne early warning information, will help minimize the number of Aegis high-energy radar acquisition dwells required to detect and establish "firm track" on ballistic threat missiles.

In addition to the DSP, the Aegis AN/SPY-1 radar may be upgraded so that the system's radar characteristics will better match the increased kinematic capabilities of the upper-tier missile. The design of an upgrade will depend on trade studies that consider the relative potential of netted theater sensors using the Aegis Cooperative Engagement Capability under development and IR sensor satellites or aircraft under conceptual development. Space or airborne IR sensors are theoretically capable of tracking ballistic missile bodies during postboost exoatmospheric flight. Both netted sensors and space or airborne IR sensors have the potential of providing target update information to the outbound upper-tier missile. In some scenarios, depending on the accuracy of these target updates, the upper-tier missiles may eventually be able to complete long-range intercepts without requiring flight update information from the firing ship's weapon control system.

COMMAND AND CONTROL TECHNOLOGIES

The recent Gulf War has given military planners and acquisition agencies a glimpse into the future of joint and coalition warfare. Joint warfare (combined service and/or allied coordinated warfighting operations) was legislated by the Goldwater-Nichols Department of Defense Reorganization Act of 1986[3] and was largely implemented under then Secretary of Defense Cheney's 1989 Defense Management Report to President Bush.[4] Operationally, the resultant changes have had their greatest impact on command, control, communications, and computer (C^4) systems. The C^4 problems uncovered during Desert Storm were circumvented where possible by innovative sailors and airmen. Since then, C^4 improvements have been initiated to help bridge the hardware and software differences between service systems.

The command and control required to support effective TMD are no less dependent on joint and allied interoperability than were the strike operations of Desert Storm. Efforts are therefore under way within the BMDO to develop the joint C^4 capacity to support the short time lines and rapid update rates required to engage TBM threats. This capacity includes the ability to disseminate rules of engagement, weapons release authority, and global sensor cueing reports in a timely and reliable manner.

The current TBMD C^4 architecture calls for the Joint Tactical Information Distribution System, a joint theater surveillance and warning communications network, to provide regional (local) connectivity. Long-range connectivity will be provided by the super-high-frequency Defense Satellite Communication System. Sensor information from the DSP will be distributed on the ultrahigh-frequency Fleet Satellite constellation to theater users via Cheyenne Mountain or alternatively via theater processing centers.

The Aegis Cooperative Engagement Capability may offer additional robustness to this architecture through its potential to provide real-time sensor data exchange and shooter-to-shooter engagement coordination. This antijam, high-data-capacity, weapon control system may be expanded to include both land and airborne air defense systems. Such an architecture may combine sea, land, and airborne theater air defense assets into a coherent theater air defense system.

SYSTEM ENGINEERING CHALLENGES

Engineering development is a truth-seeking process that must balance a continuous string of technical and programmatic decisions against competing constraints. The resulting system is a reflection of this decision-making process, which, in turn, is a function of the engineering organization's structure, individual skills, and teamwork. The BMDO's charter to develop a viable TMD system comprising space-, land-, and sea-based elements is a challenge perhaps bigger than any this nation has undertaken. The current TMD architecture requires that the space-, air-, sea-, and ground-based early warning sensors, communications systems, and air defense missile systems be selectively integrated to engage ballistic missile threats successfully across the full range of threat scenarios. This TMD system-of-systems is the combined responsibility of the BMDO Director and the service Program Executive Officers managing the individual service program development offices.

The U.S. Navy's participation in this joint development has grown significantly during the past year as the nation's leaders have recognized the potential benefits of sea-based defenses. Secretary of Defense Aspin has indicated his support for sea-based TBMD by including both the Navy lower-tier and upper-tier ballistic missile defense systems in the September 1992 DoD Bottom Up Review.

CONCLUSION

Saddam Hussein's use of Scud missiles in the Gulf War served as a wake-up call for national political and military planners. Clearly, future regional contingencies will see potential enemies threatening to use or actually firing ballistic missiles. The proliferation of increasingly accurate TBM's (possibly armed with weapons of mass destruction) requires the development of capable, mobile, and sustainable defensive systems. Naval forces can play a crucial and unique role in littoral (near-land) areas by providing protection from ballistic missiles while expeditionary forces are deploying ashore. The ability to forward-deploy TMD at sea provides an on-scene rapid response that is highly mobile and can remain on-station indefinitely. Such a capability can be extended to an extremely wide-range defense and become the sea-based component of a worldwide system.

To deploy such an air defense system, however, requires that the right combination of command, control, communications, and intelligence technologies be coupled with reliable and effective weapon system and interceptor technologies. Explosive endoatmospheric warhead and exoatmospheric or endo/exoatmospheric KKV technology must be married to dependable missile technology to create both close-in area and theater-wide interceptors. The resulting interceptors then must be launched and controlled by weapon systems that can transform early warning and fire control sensor information into high probability-of-kill TBM engagements. The development of such a TMD system-of-systems will depend on exacting and iterative engineering discipline. The complexity of such a joint service development makes it critical that the technology of systems engineering be established as a critical foundation of TMD during coming years. The complex nature of the problem will require that the Navy, Army, and Air Force work harmoniously to create a TMD system that can counter the growing ballistic missile threat.

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U.S. Navy photo

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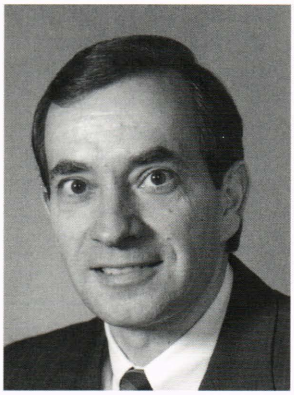

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