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Ballistic Missile Defense Effectiveness

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Abstract. The potential effectiveness of ballistic missile defenses today remains a subject of debate. After a brief discussion of terminal and boost phase defenses, this chapter will focus on long-range midcourse defenses. The problems posed by potential countermeasures to such midcourse defenses are discussed as are the sensor capabilities a defense might have available to attempt to discriminate the actual missile warhead in a countermeasures environment. The role of flight testing in assessing ballistic missile defense effectiveness is discussed. Arguments made about effectiveness by missile defense supporters and critics are summarized.

INTRODUCTION

While the debate on whether or not the United States should deploy ballistic missile defenses, in particular, a national missile defense (NMD) system, is now largely settled, the important question of how effective such systems are likely to be in actual use remains open. The answer to this question is not simple and will depend on many factors, such as the type of defense, the nature of the attacking missiles, the circumstances of the attacks, and the standards by which the success or failure of the defense is judged. Ballistic missile defense (BMD) supporters argue that defenses have already proven themselves effective in tests and in (limited) actual use. Critics argue that many of these tests are highly unrealistic and that the actual use of BMD systems has involved only the shortest-range systems and has produced mixed results.

This chapter will first briefly discuss the effectiveness of short-range within-the-atmosphere BMD systems. Its main focus, however, will be on the long-range above-the-atmosphere systems that are the main subject of debate today. Particular emphasis will be placed on the problems of midcourse countermeasures and discrimination.

TERMINAL AND BOOST-PHASE SYSTEMS

A ballistic missile's trajectory is typically divided into three phases. First, the boost phase, when the missile is under powered flight using its rocket booster. Second, the midcourse phase, in which the missile or its warhead coasts on a ballistic trajectory through the vacuum of outer space (assuming the missile's range is long enough that it leaves the atmosphere). Third, the terminal phase, in which the missile or warhead re-enters the atmosphere and falls towards its target. Each phase presents different opportunities and problems for ballistic missile defenses. Although the main focus of this chapter is on midcourse defenses, it is useful as background to first briefly discuss terminal and boost-phase defenses.

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Terminal-Phase Within-the-Atmosphere Systems

These defenses operate within the atmosphere (endo-atmospheric) in order to counter missiles as they descend towards their targets (terminal phase). A number of such BMD systems have already been deployed and several have been used in actual combat. These systems include the U.S. Army's Patriot system (with PAC-2 and PAC-3 interceptors), the U.S. Navy's Aegis system (with SM-2 Block IV and SM-6 anti-aircraft missiles), Israel's Iron Dome and David's Sling systems, and Israel's Arrow system (with Arrow-1 and Arrow-2 interceptors). All of these systems use radar for guidance and homing and most are equipped with high-explosive warheads (PAC-3 being the exception). Such defenses use aerodynamic forces for interceptor maneuvering and can also make use of atmospheric filtering to remove light-weight countermeasures. They typically cover small areas, with dimensions of tens of kilometers. In the U.S. context, defenses of this type are usually classified as theater or regional systems. They could be employed as stand-alone systems or could form a second layer of defenses operating behind midcourse defenses. They are sometimes also capable of intercepting aircraft.

The U.S. Army's Terminal High Altitude Area Defense (THAAD) is a special case. Although officially classified as a terminal phase system, its method of operation is more similar to that of a midcourse system. THAAD use an infrared-homing kill vehicle with rocket divert thrusters that maneuvers to destroy its target in a direct collision above the atmosphere. However, the THAAD kill vehicle is aerodynamically shaped and is thus also able to perform intercepts in the upper atmosphere, perhaps as low as about 40 km.

In the 1991 Gulf War, Patriot PAC-2 interceptors attempted to intercept about 44 600-km range Iraqi modified Scud missiles. Initially, the U.S. Army claimed a 96% success rate in destroying these Scuds, but after criticism from several sources, eventually reduced this claim to about 61%, where it remains today.[1] However, detailed outside technical analysis demonstrated that the actual successful intercept rate was very low, possibly zero.[2] In the 2003 Iraq War, the U.S. Army claimed that Patriot destroyed all nine short-range ballistic missiles it targeted (two using the new PAC-3 interceptor).[3]

Iron Dome was first deployed in Israel in 2011. It is a very short-range system, and is frequently described as a counter-rocket, artillery and mortar weapon. It has reportedly destroyed over 1,500 targets with an 85% success rate.[4]

The most straightforward method available to defeat endo-atmospheric interceptors is the use of vigorous atmospheric maneuvering, particularly if high missile accuracy is not needed. In 1991, the Iraqi Scuds broke apart before or on atmospheric re-entry, with the warhead section cork-screwing through the lower atmosphere – maneuvers that the Patriot PAC-2 interceptor could not cope with. The subsequent PAC-3 interceptor was designed to be much more maneuverable, using small rocket thrusters along the missile body to generate very rapid attitude changes and aerodynamic forces. It does not appear that the Iron Dome targets maneuvered significantly. How current terminal BMD systems would fare against targets similar to the 1991 Scuds is unclear, as there is no publicly available data (such as test results) that could be used to assess their likely performance.

Boost-Phase Defenses

Boost-phase defenses attempt to destroy missiles while they are still in powered flight. By destroying a missile's rocket booster before it has finished burning, its warhead will fall short of its intended target, although it is possible it could still explode. A boost-phase defense could use hit-to-kill interceptors, or because rocket boosters are much more fragile than missile warheads, beam weapons such as lasers.

Boost-phase defenses have some significant advantages relative to midcourse defenses. First, since destroying a missile during boost phase eliminates all of its warheads, boost-phase defenses are desirable against missiles equipped with multiple warheads. Boost-phase defenses are the only type of ballistic missile defense (leaving aside pre-emptive measures) that can counter conventional, chemical, or biological submunitions. Large numbers of submunitions released immediately after the end of boost phase will overwhelm any midcourse or terminal defense.

Second, the problem of countermeasures appears to be much less severe for boost-phase defenses than it is for midcourse defenses. While some types of countermeasures – such as various forms of trajectory modification (against homing interceptors) or reflective coatings (against lasers) – are feasible, their scope and effectiveness appear to be more limited than that of the wide range of potentially very effective midcourse countermeasures.

The greatest difficulty facing boost-phase defenses is that the boost phase of a ballistic missile is at most a few minutes long. This means that a boost-phase interceptor must have a very high speed and acceleration, and must also be based relatively close to an attacking missile's launch location.[5] Even so, they are likely to be practicable only against liquid-fueled long-range missiles with long burn times.[6] The need to be close to the launch site limits their potential utility to use against relatively small countries, such as North Korea or possibly Iran. While space-based interceptors or lasers have been proposed to get around this limitation, they would be prohibitively expensive.

These considerations have so far prevented the deployment of any boost-phase systems. The United States cancelled its two most recent boost-phase development programs, the Kinetic Energy Interceptor, which was too slow, and the Airborne Laser, which had inadequate range among other problems, in 2009 and 2011, respectively. The Missile Defense Agency is now developing several types of electrically-driven lasers with the objective of deploying one of them as a boost-phase weapon on an unmanned aerial vehicle in the mid-2020s.

LONG-RANGE EXO-ATMOSPHERIC MIDCOURSE DEFENSES

Long-range midcourse defenses are the primary focus of this chapter. They operate above the atmosphere (exo-atmospheric) and use direct collisions by infrared-homing hit-to-kill kill vehicles to destroy their target missiles' warheads as they travel through the vacuum of outer space. The term "midcourse" refers to the part of the target's trajectory after its booster rocket has burned out but before it begins to re-enter the atmosphere. Midcourse defenses are in principle capable of defending large geographic areas, with dimensions of hundreds to thousands of kilometers. However, their exo-atmospheric mode of operation makes them potentially vulnerable to defeat by a variety of light-weight above-the-atmosphere countermeasures. A primary objective of such defenses is countering nuclear-armed missiles, and in this role their effectiveness must meet very stringent criteria. During the Cold War, such defenses would have been considered strategic defenses, although they now have regional roles as well.

The United States currently has two midcourse missile defense systems, the Ground-Based Midcourse Defense (GMD) NMD system and the U.S. Navy's SM-3 Aegis BMD system. The U.S. Army's THAAD system also has some limited midcourse capabilities, but it will not be considered further here.

The Ground-Based Midcourse Defense System

The GMD system is a national missile defense system; that is, it is intended to defend U.S. territory from long-range ballistic missile attacks. In principle, it is capable of covering all fifty states from missiles launched from North Korea or Iran. The interceptor of the GMD system is the Ground Based Interceptor (GBI), an ICBM-sized missile deployed in silos at Fort Greely in central Alaska and at Vandenberg Air Force Base in California. The first GBI was deployed in July 2004 and the GMD system was declared operational later that year. Current plans a call for a total of 44 GBIs to be deployed by the end of 2017 (40 of them Alaska). The deployment of an additional interceptor site in the eastern United States is under consideration.

The 16.6 m long GBI's purpose is to deliver a roughly meter long, 55 kg Exo-atmospheric Kill Vehicle (EKV) to an intercept trajectory for an incoming missile warhead. After release from the GBI, the EKV detects the target using an infrared sensor, and maneuvers itself to intercept it using four small rocket divert thrusters. There are several generally similar versions of the EKV currently deployed; the most recent, the CE-II Block I EKV, had its first intercept test (a success) in May 2017. Due to its hasty development process, the EKV's reliability is poor, and beginning in 2020 the U.S. Missile Defense Agency (MDA) intends to begin replacing the EKVs with new Redesigned Kill Vehicles (RKVs).

The GBIs are supported by a network of large phased-array radars at Shemya in the Aleutians; in California; in central Alaska; on Cape Cod; at Thule, Greenland; and at Fylingdales in Britain. Although these are large and powerful radars capable of tracking many targets simultaneously at long ranges, they have little capability to discriminate actual warheads from decoys or other objects. Much smaller forward-based X-band TPY-2 radars in Japan and Turkey and Aegis radars on BMD-capable Navy destroyers and cruisers also support the GMD system (X-band extends from 8 to 12 GHZ, and is often taken to mean about 10 GHz.).

The GMD system's primary discrimination sensor is a large X-band radar on a modified ocean-going oil drilling platform. The radar, known as the Sea-Based X-band (SBX) radar, operates out of Honolulu and has sailed west on several occasions to observe anticipated North Korean missile flight tests. It has significant operational limitations, most notably a very limited electronic-scan field-of view (about ±12°, compared to about ±60° for a typical phased-array radar). By 2020 the MDA plans to deploy a new S-band Long Range Discrimination Radar (LRDR) in central Alaska (S-band extends from 2 to 4 GHz). The GMD system is also supported by a highly effective space-based infrared-detecting missile launch early warning system.

The SM-3 Aegis Ballistic Missile Defense System

The U.S. Navy's Aegis BMD system is based on the Aegis combat system on its cruisers and most of its destroyers. The Aegis system includes the Aegis computers and software, the four-faced SPY-1 phased-array radar, and a large number of vertical launching tubes (90-96 in the destroyers, 122 in the cruisers). In addition to BMD interceptors, the vertical launchers carry a mix of weapons including SM-2 anti-aircraft missiles, SM-6 long-range anti-aircraft missiles (which can also attack surface targets and short-range ballistic missiles), Tomahawk land-attack cruise missiles, and anti-submarine weapons.

As of mid-2017, the Navy had 22 cruisers and 63 destroyers equipped with the Aegis system. For a number of years the Navy has been upgrading Aegis ships to give them ballistic missile defense capabilities. As of mid-2017 about 35 ships had received some form of BMD upgrade; only a few, however, have what the Navy calls the "advanced" BMD capability, which allows them to perform ballistic missile defense and air defense simultaneously. At present, the Navy is upgrading ships to the advanced capability at a rate of about two per year. In addition, all new construction Aegis destroyers will be delivered (also at about two per year) with the advanced BMD capability built in.

The midcourse BMD interceptors currently deployed on Aegis BMD ships are the SM-3 Block IA and SM-3 Block IB missiles. These missiles are kinematically similar, with a burnout speed believed to be about 3 km/second. After their booster burns out and they leave the atmosphere, the interceptors release a small infrared-homing kill vehicle that attempts to destroy its target in a direct high-speed collision. Although these interceptors work in exactly the same manner as the GBIs of the national missile defense system, their much lower speed prevents them from being able to cover enough territory to be useful for a strategic defense of U.S. territory.

In 2018, however, the United States plans to begin deployment of the new SM-3 Block IIA interceptor. This interceptor will have a much higher burnout speed of about 4.5 km/s. This higher speed will enable it to cover much larger geographic areas, particularly when deployed near the target areas, so that the interceptor has more flight time available. In order to achieve this large area coverage, Aegis BMD will need to use its engage-on-remote capability, which allows its interceptors to be guided by external sensors (such as those of the GMD system).

CLAIMS ABOUT DEFENSE EFFECTIVENESS

According to many missile defense proponents, effective ballistic missile defenses are already an established fact. In March 2013, in discussing the GMD NMD system, Secretary of Defense Chuck Hagel stated that "…the American people should be assured that our interceptors are effective."[7] Three months earlier, his predecessor, Leon Panetta, in response to a question about a potential North Korean missile attack, stated that "I'm very confident that American defense capabilities are able, no problem, to block a rocket like this one."[8] Missile defense supporters also cite Israeli claims that their Iron Dome system is already achieving success rates of as high as 85-90% against short-range rockets as proof that missile defenses can work.

Critics argue that ballistic missile defenses, particularly those that operate above the atmosphere, are vulnerable to defeat by a wide range of simple countermeasures, and that this vulnerability has been known for decades yet remains an unsolved problem. They point out that missile defense test programs are highly artificial and scripted, and reveal little about how well the defenses would work in the real world. In their view, the Iron Dome experience against short-range rockets within the atmosphere has essentially no relevance to midcourse defenses against longer-range missiles.

WHAT DOES IT MEAN TO WORK?

What does it mean to say a missile defense system can or does “work”? How effective must a defense be in order to be meet its objectives? What fraction of attacking warheads should it be expected or required to destroy? There is no simple answer to these questions, since any answer is highly circumstance-dependent.

Israeli experiences with missile defenses illustrate the complexity of this problem. The performance of Iron Dome in 2012-2014 has been widely hailed as a success for ballistic missile defenses, and in particular for reducing the pressure on the Israeli military to respond to the rocket attacks in other, potentially much more escalatory, ways. However, a similar argument could be made that Patriot in 1991 was successful in preventing potentially coalition-fracturing Israeli strikes against the Iraqi Scud launchers. Yet while Patriot was widely perceived during the Gulf War as being highly effective, its actual effectiveness in destroying Scuds was essentially zero.[9] Moreover, few would argue that the claimed Iron Dome failure rate of about 10-15% would be adequate against an attack by more than a few nuclear-armed missiles.

Statements from U.S. officials suggest, however, that a system intended to counter nuclear-armed missiles could be considered effective if its predicted effectiveness is greater than about 90%. On June 16, 2009, just a week after Defense Secretary Robert M. Gates told Congress that the current GMD NMD system was “fully adequate to protect us against a North Korean threat,” General James Cartwright, Vice Chairman of the Joint Chiefs of Staff, told a Senate committee that he assessed the effectiveness of the GMD system against a North Korean missile as “ninety percent, plus.”[10] A year later, amid continuing statements by U.S. officials about their confidence in the effectiveness of the GMD system, MDA Director Lt. Gen. Patrick O’Reilly told the House Armed Services Committee that the probability that the system could counter a single ICBM launched by Iran “would be well over into the high nineties.”[11]

RELIABILITY AND OPERATIONAL EFFECTIVENESS

The fundamental issue with midcourse missile defense effectiveness is not whether the defenses can work in principle or how well they might work on a test range. It is their operational effectiveness – that is, how well they can be expected to work on the battlefield, where unexpected circumstances and enemy measures to defeat the defense must be expected.

It is important to distinguish the operational effectiveness of a midcourse defense system from its reliability. Current midcourse defense intercept tests are essentially highly-scripted demonstrations designed to verify computer simulations of the defense’s performance. As such, their success or failure primarily reflects the reliability of the systems being tested. Determining the operational effectiveness of a defense is a much more complex problem, which at a minimum requires establishing the ability of the defense to handle the full range of conditions, including plausible enemy countermeasures, it could face in actual use. The operational effectiveness of a midcourse missile defense system is difficult to assess for several reasons.

First, there is no real-world experience with the use of midcourse ballistic missile defenses. The only actual uses of ballistic missile defenses are of terminal, endo-atmospheric defenses (Patriot and Iron Dome) against short-range missiles and rockets. Not only are the outcomes of these experiences mixed, but they likely have little relevance to exo-atmospheric defenses against longer-range missiles, which are the primary focus of the current debate over ballistic missile defenses. It is possible that there will never be a significant body of real-world experience with midcourse defenses against long-range ballistic missiles, particularly in a nuclear environment

Second, there is no consensus on the nature of long-range ballistic missile threats, particularly regarding the potential use and effectiveness of steps to defeat defenses (countermeasures). For example, official claims of the effectiveness of the U.S. GMD national missile defense system assume that the missile threat it faces is the one that could exist in the near future – one that does not include any effective countermeasures. Missile defense critics argue that future missile threats must be expected to include simple yet highly effective countermeasures that could be difficult for existing or planned defenses to defeat. Missile defense supporters counter that effective countermeasures are not easy to employ and that future technical development of missile defenses will enable them to defeat countermeasures as they emerge.

Third, midcourse missile defense tests are complex and expensive. The most recent GMD test, FTG-15 in May 2017, cost $244 million.[12] The cost and complexity of the tests limits the number and frequency of tests, making it difficult to test over the full range of circumstances that the defense might expect to encounter. In this situation, a single test failure can cause severe setbacks for a missile defense development program.

Finally, the technical nature of ballistic missile defenses and the secrecy associated with some aspects of them inhibit informed public assessment and discussion of the actual and potential effectiveness of midcourse missile defenses. For example, in May 2002 the Missile Defense Agency announced that all details about future GMD test targets would be classified.[13]

THE PROBLEM OF MIDCOURSE COUNTERMEASURES

Enemy steps intended to defeat a missile defense, generally referred to as "countermeasures," have been the most fundamental problem facing midcourse ballistic missile defenses from their beginning, and remain so today. The prospects for defeating countermeasures, often narrowly described as "discrimination," is the most controversial technical issue involving midcourse defenses.

Several aspects of operating in the exo-atmosphere make midcourse defenses particularly vulnerable to countermeasures. In the vacuum of outer space, heavy and light objects released from a missile will travel on (nearly) identical trajectories. The lack of wind resistance allows objects with little structural strength to retain their shape. Taken together, these two factors enable a wide range of lightweight countermeasures. In addition, objects in space gain or lose energy only through radiation, allowing manipulation of their surface temperatures. For example, a sunlit spherical balloon in Earth orbit with an aluminum foil (shiny side) surface coating will have an equilibrium temperature of 454 K, while one with a white epoxy paint coating will have an equilibrium temperature of 237 K.[14] Any equilibrium temperature between these two can be achieved by covering varying proportion of the aluminum foil surface with dots of white paint. Non-sunlit spherical objects have an equilibrium temperature of about 180 K for all surface coatings.

Two recent major U.S. government-sponsored technical studies highlighted both the importance and the difficulty of discrimination. A 2011 report by the Department of Defense's Defense Science Board stated that "The importance of achieving reliable midcourse discrimination cannot be overemphasized."[15] The report went on to conclude: "Yet discrimination in the exo-atmosphere is still not a completely solved problem. Robust research and testing of discrimination techniques must remain a high priority."[16] A 2012 study by the National Academy of Sciences (NAS) concluded that "The hard fact is that no practical missile defense system can avoid the need for midcourse discrimination – that is, the requirement to identify the actual threat objects (warheads) amid the cloud of material accompanying them in the vacuum of space. This discrimination is not the only challenge for midcourse defense, but it is the most formidable one, and the midcourse discrimination problem must be addressed far more seriously if reasonable confidence is to be achieved."[17]

Countermeasures are not just a hypothetical possibility. All five of the first nuclear-weapon states have developed and, at least in some cases, deployed countermeasures on their nuclear-armed intercontinental ballistic missiles (ICBMs) or submarine-launched ballistic missiles (SLBMs).[18] Eighteen years ago, a U.S. national intelligence estimate concluded that "We assess that countries developing ballistic missiles would also develop various responses to US theater and national defenses. Russia and China each have developed numerous countermeasures and probably are willing to sell the requisite technologies."[19] More specifically, the estimate stated that "Many countries, such as North Korea, Iran, and Iraq probably would rely initially on readily available technology – including separating RVs, spin-stabilized RVs, RV reorientation, radar absorbing materials (RAM), booster fragmentation, low-power jammers, and simple (balloon) decoys – to develop penetration aids and countermeasures" and that "These countries could develop countermeasures based on these technologies by the time they flight test their missiles."

There are many possible exo-atmospheric countermeasures. Examples include replica decoys, electronic decoys, booster fragmentation, enveloping structures or screens, radar stealth, jammers, infrared stealth (low emissivity coatings or cooled shrouds), obscurants (radar chaff or aerosols), midcourse maneuvers, nuclear detonations to create electromagnetic pulse effects, and direct attacks on ground-based defense components (such as radars). Multiple countermeasures can be used in combination to enhance their effectiveness.

Two Countermeasure Approaches

As an illustration of the potential difficulties facing a system attempting discrimination, consider two potential approaches to using decoys: booster fragmentation and enveloping balloons. One might think that a decoy should be designed to have an appearance and dynamics as similar to the real warhead as possible. Such decoys are known as replica decoys, and it is known that the United States has developed and tested such decoys. For example, in 1971 it flight-tested the Inflatable Exoatmospheric Object, a replica decoy for the Mark-12 reentry vehicles on Minuteman ICBMs.[20] Replica decoys were also developed as targets for missile defense tests.[21]

With a replica decoy, however, there is a risk that the defender might be able to exploit a small discrepancy between the decoy and the real warhead to identify the warhead. In addition, to closely mimic all the characteristics of the real warhead might result in the decoy mass being higher than desired. A potentially more effective alternative approach would be to instead make the warhead look like a decoy – an approach known as anti-simulation.

One such anti-simulation approach is booster fragmentation. In this approach, the final stage of the warhead's rocket booster would be cut up, using explosive cutting cords or other methods, into numerous pieces comparable to or larger in size than the warhead. In 1975, the U.S. Army conducted a missile flight test, designated Signature of Fragmented Tanks, in which the second stage of a Titan II ICBM was fragmented, as intended, into 28 pieces.[22] This test was used to test the ability of the Safeguard Anti-Ballistic Missile radar in North Dakota to distinguish between the fragments and a warhead (it does not appear to be publicly known if the radar was able to do so). If the warhead itself was then disguised to look like debris, for example, by attaching several crumpled sheets of aluminum foil to it, the defense would then be confronted by a large number of possible targets, none of which look like a warhead.

Another anti-simulation approach is to enclose the warhead in a balloon with a thin metal coating and release it along with a large number of similar but empty balloons. The metal coating would prevent radars from observing what was inside the balloons and their temperatures could be manipulated using coatings over the metallic layer and by varying the shapes of the balloons (or by putting a small heater in some of the empty balloons). Making the shape and surface coating different for each balloon prevents the defense from singling out one balloon – the one with the warhead – as different from all the others. A 1999 report discusses this enveloping balloon countermeasure in detail.[23] The Chevaline countermeasure system developed by Britain in the 1970s for its Polaris submarine-launched ballistic missiles reportedly enclosed both of its two warheads in metallized balloons and released them along with balloons containing decoy warheads and empty balloons.[24]

Sensors for Midcourse Discrimination

Current midcourse defenses have two types of data available with which to attempt to perform discrimination: measurements from the kill vehicle's infrared sensors as it closes in on the threat cloud and measurements from ground-based radars.

For almost the entire homing process, the kill vehicle's infrared sensors will see a warhead-sized target (about 2 m long) as only a single pixel. For a 256 x 256 array with a one degree field of view, the field-of-view of a single pixel will reach 2 m only at a range of about 30 km, when at a typical closing speed of 10 km/s the kill vehicle is only 3 seconds from impact. The actual shape of the target that the kill vehicle is homing in on will not become apparent until the kill vehicle is roughly a second or less from impact. Such rough information on the shape of an object may or may not be helpful in discrimination, depending on the nature of the countermeasures used by the attacker.

At longer ranges, where each target appears only as a single pixel, the kill vehicle's two-color infrared sensor can in principle be used to measure the temperature and emissivity-area product of each object in the threat cloud. This assumes that each object has a well-defined temperature (for example, a sunlit balloon painted with broad stripes might not) and that there is no more than one object per pixel. Again, as discussed above, the attacker has some control over the temperature of the objects the missile deploys, and it is at best unclear how these measurements could be used to distinguish between different object comparable in size to the warhead.

The MDA is interested in deploying infrared sensors on high-altitude unpiloted aerial vehicles for midcourse tracking. Such UAVs could potentially be positioned so as to provide infrared data well before a sensor on a kill vehicle could. However, given the range from the UAV to the threat cloud will almost always be at least several hundred kilometers, each object in the threat cloud will always appear as no more than one or two pixels and closely-spaced objects could not be resolved. Thus while such UAVs may be able to provide useful tracking data, they cannot be expected to contribute significantly to discrimination.

Given the limitations of the GMD system's infrared sensors, against any but the least effective countermeasures the burden of discrimination will fall on its radars. A key measure of the discrimination capability of a radar is its range resolution, which is typically orders of magnitude better than its resolution in directions perpendicular to the range axis. The range resolution ΔR of a radar is approximately given by $\Delta R \approx c/2\beta$, where c is the speed of light and β is the radar's bandwidth.[25] For a phased array radar, its bandwidth is typically limited to about 10% of the radar's operating frequency.

The large phased-array early warning radars that were upgraded to provide the initial core radar capability of the GMD system operate at between 420 and 450 MHz. As originally built, they had maximum bandwidths that varied by radar between 1 and 10 MHz.[26] It is possible that as part of the upgrade process to incorporate them into the GMD system, their bandwidth might have been expanded to span their full operating band of 30 MHz. Even so, their range resolution would only be about 5 m, not small enough to provide much information beyond the target's radar cross section and how it varied with time, and these radars thus had little if any discrimination capabilities.

The limited discrimination capabilities of the upgraded early-warning radars is described in a 2004 Government Accountability Office assessment of the first two of them to be integrated into the GMD system: "Neither the Cobra Dane radar nor the upgraded early warning radar at Beale is capable of performing rigorous discrimination, a function acheivable only by the X-band radar. Rather, both radars will utilize common 'target classification' software that enables them to classify objects as threatening or non-threatening. For example, debris would be classified as non-threatening, but objects like deployment buses and decoy replicas would be classified as threatening."[27]

As discussed above, the primary radar discrimination sensor of the current GMD system is the SBX, which operates in the X-band (8–12 gigahertz) of radar frequencies. The SBX is often assumed to have a center operating frequency of about 9.5 GHz, or a center wavelength of about 3.16 centimeters (1.2 inches). It has a bandwidth of about 1.0 GHz, and a range resolution of about 25 cm or somewhat better.[28] The much smaller TPY-2 radars, which operate as forward-based radars for the GMD as well as the radars for THAAD batteries, have similar frequency and bandwidth characteristics. These X-band radars can thus measure features along a target in the range direction with a resolution of about 25 cm, which, depending on the circumstance, may or may not be useful for discrimination.

In addition, if a target has rotational motion relative to the radar, radars such as the SBX and TPY-2 can use the Doppler shift produced by this rotation to obtain resolution in a direction perpendicular to the range axis. This resolution ΔR_A is given by $\Delta R_A = \lambda/2\theta_R$, where λ is the radar wavelength and θ_R is the angle rotated through during the observation period.[29] Thus for a radar operating at 9.5 GHz with a range resolution of 25 cm, a target rotation of 0.063 rad = 3.6° perpendicular to the radar line of sight is needed to get a cross-range resolution equal to the range resolution.

The NAS report concludes that by using multiple high-resolution radars, long observation times, and techniques such as range-Doppler imaging, "…an adequate level of discrimination performance can be achieved in the near term and that this approach has a reasonable chance of keeping the United States generally ahead in the contest between countermeasures and counter-countermeasures."[30] However, the detailed analysis supporting this claim is classified, as are the type and sophistication of the countermeasures considered.

TESTING

The most direct and visible indicator of the effectiveness of a BMD system is its performance on the test range. If a BMD system performs poorly on the test range, then it is unlikely to work well in actual use. On the other hand, a system that performs well on the test range may or may not work well in combat. The key issue here is how realistic the testing is. An example is the Patriot missile in the 1991 Gulf War. Prior to the war, Patriot was a perfect 17 for 17 in tests, but in the war it performed poorly, destroying few if any of the 44 Scuds it attempted to intercept. The Scuds the Patriot system encountered in the war were faster than the ones it was tested against and, unlike the test targets that flew on stable trajectories, they maneuvered vigorously as they fell.

How can the effectiveness of a midcourse BMD system be established? One way to look at this problem is to break it down into a series of increasingly difficult criteria the BMD system must demonstrate it can meet in order to establish that it will work in actual combat conditions. In actual practice, these steps are likely to overlap.

For example, for a midcourse system, the first criterion would be to demonstrate the feasibility of the basic principles of midcourse exo-atmospheric infrared-homing hit-to-kill interception. Although many intercept tests have failed, the United States has already completed about 40 successful midcourse intercept tests (as of July 1, 2017), so this criterion can be regarded as having been met. The second step would be for a specific system to demonstrate that it can perform reliably under simple and controlled conditions. As Tables 1 and 2 below show, the GMD system clearly has not yet met this criterion, while the Aegis BMD system may have, at least for the Block IA and Block IB interceptors.

TABLE 1. Intercept test record for the U.S. Ground Based Midcourse system, organized by the type of exo-atmospheric kill vehicle used in the test, as of July 1, 2017.

Kill Vehicle Type	Number of Tests	Successful Intercepts	Success Rate
Prototypes	10	5	50%
CE-I	4	2-3	25-50%
CE-II	3	1	33%
CE-II Block I	1	1	100%
Total	18	9-10	50-56%

TABLE 2. Intercept test record for the U.S. Navy's Aegis BMD system's SM-3 interceptor, organized by the version of the interceptor used in the test, as of July 1, 2017.

Interceptor Type	Number of Tests	Successful Intercepts	Success Rate
Block 0 – Block 1	7	5	71%
Block IA	19	16	84%
Block IB	9	7	78%
Block IIA	2	1	50%

Table 1 shows that the GMD system has only succeeded in about half of its intercept tests and, further, that its success rate is not improving over time. (The reason for the two values for GMD CE-I tests is that, in one test, the kill vehicle delivered a "glancing blow" to the target rather than a direct hit. Although the MDA classifies this intercept as a success, the Pentagon's Director of Operational Test and Evaluation scored it as "not a kill." [31])

On the other hand, the Aegis BMD system has a combined overall success rate of about 82% for its Block I interceptors. This might be considered to be high enough to establish reliable performance, although a higher success rate is both desirable and possible (THAAD is 14 for 14 in tests (as of July 15, 2017) since it resumed testing in 2006, although most of the tests were not exo-atmospheric).

The third step would be to demonstrate that the system could maintain this reliable performance over a wide range of potential operating circumstances. Even if it had demonstrated reliable performance, the GMD system would fall far short on this criterion. Although the GMD system is primarily a defense against ICBMs, it has only been tested once against an ICBM-range target, in May 2017. It has never been tested at night – all its targets have been sunlit. Although the GMD is intended to operate in a salvo mode, in which multiple interceptors are fired at the target before the outcome of the first intercept attempt is known, it has never been tested in salvo mode. Nor has it ever been tested against more than one near-simultaneous targets.

Aegis BMD appears to do much better on this third criterion. It has been tested both during daytime and at night. It has been tested against short-, medium-, and intermediate range targets (the SM-3 Block I interceptors are not intended to intercept ICBMs). It has been tested against both intact missiles and against separated warheads. It has been tested against two near-simultaneous targets.

The fourth, final, and most difficult step would be to demonstrate reliable performance against a wide range of plausible countermeasures. Although the secrecy associated with the countermeasures used in testing makes this criterion difficult to assess, as discussed in the next section, it seems likely that current testing has not progressed beyond the simplest of countermeasures.

GMD Test Targets

Has the testing of U.S. midcourse defenses been realistic? If, not, when can we plausibly expect it to be? The GMD is the U.S. midcourse system for which the most detailed information about its testing is available, and the nature of the targets it has been tested against is described below.

The GMD program's first intercept test took place in October 1999. Prior to that test, in 1997 and 1998, MDA conducted two GMD flyby tests. In a flyby test, the interceptor's kill vehicle observes and collects data on the target warhead and threat cloud as it flies by them but does not attempt to intercept the target. In each flyby test, the target threat cloud consisted of the warhead target plus eight decoys which included both round and conical objects.[32] At least one of the spherical objects had stripes on its surface, so it would produce a fluctuating signal. Although the Ballistic Missile Defense Organization (BMDO, the former name of the current Missile Defense Agency) claimed the flyby tests had been successful, and that the kill vehicles would have been able to distinguish the warhead from the decoys (the discrimination analysis was done on the ground following the tests), a whistleblower claimed that in the first flyby test the data was improperly manipulated to get the desired result.[33]

In 2000, the *New York Times* published a BMDO chart showing the actual and planned target sets for the two flyby tests and first 19 GMD intercept tests as of May 5, 2000.[34] As of the date of this chart, the two flyby tests and the first two intercept tests had been completed. The chart shows that after the flyby tests, no conical or striped objects were to be used, leaving as decoys only spherical, uniform objects that did not resemble the conical warhead targets.

In the first five of these tests, IFT-3 (October 2, 1999) through IFT-7 (December 3, 2001), the threat cloud included two other objects in addition to the conically shaped warhead target: a large (1.7–2.2 meter diameter) balloon decoy, and the final rocket stage used to deploy them.[35] (Early flight tests with interceptors using prototype or surrogate components were given an IFT designation; later tests using operationally-configured interceptors used an FTG designation.) Due to its larger surface area, the balloon had a much larger infrared emission signal than the warhead target, allowing the two to be easily distinguished from each other. According to Brigadier General Willie B. Nance, the program manager for national missile defense at the BMDO, the target warhead "was the least visible in the IR spectrum of all the elements in the target array, and the smallest of all the objects in the target array."[36] In the 6th intercept test, IFT-8 (March 15, 2002), two small balloons with infrared signals much smaller than the warhead target were also added to the threat cloud.

In May 2002, the MDA announced that details about GMD test targets would be classified for all future GMD tests.[37] The intercept test after that announcement, IFT-9 (October 14, 2002) apparently used a threat cloud similar to that of IFT-8, with one large and two small balloons in addition to the target.[38] The BMDO planning figure published in the *New York Times* in June 2000 indicated that subsequent intercept tests would use similar target sets as their threat clouds.[39] In any event, in the three remaining tests in the IFT series (IFT-10, IFT-13C, and IFT-14), the GBI interceptor or its launcher failed before it reached the point at which the kill vehicle would have been able to observe the threat cloud.

It should be evident that the tests described above are not demonstrating any real discrimination capability. Rather, they are only demonstrating the ability of the kill vehicle to distinguish between objects with different infrared brightnesses and to home in on the one with the relative brightness that matches the information preprogrammed into the kill vehicle. The *New York Times* chart shows that, at least for the first 19 intercept tests, the BMDO did not plan to move beyond such simple targets. (Although the chart shows the 19th intercept test occurring in May 2005, in actuality the 19th intercept test did not take place until May 2017.)

The secrecy associated with both the nature of the countermeasures expected and the countermeasures actually used in the tests allows military and industry officials to claim that tests against even the simplest of targets demonstrate a robust real-world capability. Recall that the target threat cloud in the first intercept test consisted of the target warhead, a two meter diameter spherical balloon, and the bus used to deploy the target and the balloon. While such a simplistic threat cloud was appropriate for an early test, John Peller, vice-president and NMD program manager at Boeing, stated that the "…target suite was equal to, if not more challenging than, the current projected rogue threat.[40] An unnamed Pentagon official claimed that this target suite was more than threat-representative of a rogue state.[41]

ARGUMENTS ABOUT EFFECTIVENESS BY MISSILE DEFENSE ADVOCATES

Missile defense supporters argue that developing and deploying countermeasures in actual practice is more difficult than critics claim, and in particular they cite past U.S. difficulties encountered in developing and deploying countermeasures. According to the 2012 NAS report "One should avoid overstating the ease with which countermeasures that are theoretically possible can actually be made to work in practice…" and "It is perhaps noteworthy that U.S. (and U.K.) experience with the development of high-confidence penetration aids during the Cold War was of mixed success."[42] Missile defense advocates also point out that deployment of countermeasures will impose penalties in terms of payload, range, and/or reliability on missiles that may already have only marginal capabilities.

Missile defense supporters also argue that countermeasures would require lengthy and visible testing programs that would allow time to develop counter-countermeasures. Responding to the 2000 *Countermeasures* report, MDA director Lt. General Ronald Kadish stated that a country "would not be capable of testing the chosen countermeasures without revealing telltale characteristics to the NMD system."[43]

Missile defense supporters further argue that the current missile threat does not yet include anything but the simplest countermeasures, and the capability of missile defenses to cope with countermeasures will increase as they are further developed. In particular, they emphasize the countermeasure against counter-countermeasure contest is an ongoing competition in which U.S. technological advantages will allow it to stay ahead of any country such as North Korea or Iran. Thus the 2012 NAS report concluded that "…an adequate level of discrimination performance can – in the committee's judgment – be achieved in the near term and provide a reasonable chance of keeping the United States generally ahead in the contest between countermeasures and counter-countermeasures over time, at least against emerging missile states like North Korea and Iran."[44]

Missile defense advocates argue that strategies for structuring and operating defenses will enhance effectiveness, for example, multiple defense layers, firing multiple interceptors at each missile, and operating strategies such as shoot-look-shoot, in which the outcome of a first intercept attempt is observed before possibly firing a second interceptor.

Missile defense supporters also argue that advances in sensor technologies – in particular, wide bandwidth X-band radars and advanced infrared imaging sensors – will enable a defense to collect information that can be used to discriminate warheads. The 2012 NAS report's conclusion about radar discrimination is that "by observation over the longest possible time by X-band radars," an "adequate solution of the problem [radar discrimination] is possible."[45] More generally, the report concludes that by using all possible sensor information over the longest time intervals possible, "an adequate level of discrimination performance can be achieved in the near term."[46]

Missile defense advocates also frequently claim that critics do not have access to classified information that shows that defenses will be effective. Responding to the 2000 *Countermeasures* report, MDA Director Lt. General Kadish argued that "I would like to emphasize the fact that many of the discrimination technologies and techniques the proposed NMD system relies on cannot be discussed in an open forum.[47] While the NAS report stated that the committee believed the problem of radar discrimination was solvable, the discussion justifying this conclusion was in a classified appendix.[48]

Finally, while missile defense supporters acknowledge the importance of realistic testing, they argue that with modern BMD systems, the primary purpose of testing is to validate computer simulations of the defense's performance, so extremely frequent testing is not required, nor is testing against all possible target configurations necessary.

ARGUMENTS ABOUT EFFECTIVENESS BY MISSILE DEFENSE CRITICS

Missile defense critics argue that the employment of potentially effective countermeasures must be expected. It is unrealistic to think that a country that is capable of building both a nuclear warhead small and rugged enough to be deliverable by a missile and an intercontinental ballistic missile and reentry system capable of delivering such a warhead will not be able to take relatively simple steps such as deploying the warhead inside a balloon along with a number of empty balloons. Given that nuclear weapons are likely to be an extremely limited and valuable resource to countries such as North Korea, and the known existence of ballistic missile defenses, such countries will have powerful incentives to take steps to enhance the likelihood that their nuclear-armed missiles can penetrate a defense.

Missile defense critics dismiss claims that the United States had significant problems developing countermeasures during the Cold War as irrelevant, since such countermeasures would have had to defeat a nuclear-armed defense, a far more difficult problem than today's or tomorrow's missile attacker would face. Moreover, even though limited to 1960s or 1970s technologies, potentially very effective countermeasures were developed. An example is the countermeasures package planned in the late 1950s for the British Blue Streak medium-range ballistic missile, which was ultimately never deployed. Each missile was expected to carry 20-40 decoys, which, together with electronic jammers, would be dispersed in a spherical cloud with a diameter of roughly 30 km.

According to one British defense scientist at the time, “as regards invulnerability it is so advanced that neither the U.S. nor ourselves can conceive of a counter to it.”[49]

In addition, missile defense critics point out that there are many possible types of countermeasures which can be used in many combinations. An attacker need only find one combination of countermeasures that it believes it will be effective, whereas if a defense is to be relied upon, it must be able to defeat all plausible countermeasures. Moreover, attacks by long-range, nuclear-armed missiles are likely to be extremely rare events. Thus not only must a defense work extremely well, but it must do so the first time it is ever used, a difficult criterion to meet.

Critics also argue that it is unrealistic to expect countries such as North Korea to require anything like the same level of testing, reliability, or confidence in their systems that the United States would require in military systems. They note that for many years the United States has regarded North Korean missiles as an imminent threat to U.S. territory, even though North Korea had never successfully flight-tested a ballistic missile with intercontinental range. (In July 2017 North Korea flew a missile on a lofted trajectory that might have had intercontinental range if flown on a maximum-range trajectory.)

Firing multiple interceptors at the threat cloud from each missile is not only possible, but will likely be required to get an acceptable level of effectiveness even against a missile not equipped with countermeasures. However, if a first intercept attempt fails because of a countermeasure – not because of an interceptor reliability problem – then the same countermeasure could well also be successful against a second and subsequent intercept attempts.

While a shoot-look-shoot strategy is likely be desirable if timelines permit it, it does not increase the defense’s effectiveness against small attacks, it only allocates interceptors more efficiently. If two interceptors are fired at a missile, the probability of a successful intercept will be same regardless of whether the interceptors are salvo-fired or fired using a shoot-look-shoot doctrine. However, if the first intercept is successful, the shoot-look-shoot approach will only expend one instead of two interceptors.

While multiple layers operating using different principles can in principle improve overall effectiveness, there are significant limitations in practice. No country has deployed a boost-phase layer, and a terminal within-the-atmosphere layer can only cover limited geographic areas relative to a midcourse defense. Thus while a geographically small country might be able to employ a multi-layered defense, this would be much more difficult for a large country such as the United States. The current GMD NMD system consists of only a single layer. Adding another wide-area defense system, such one based on the Navy’s new SM-3 Block IIA interceptor, while feasible, would only add a system with exactly the same vulnerabilities to countermeasures as the GMD system.

Finally, critics point out that the effectiveness of many types of countermeasures are based on fundamental physical principles (such the inability of radar waves to penetrated even extremely thin metallic layers), and thus their effectiveness does not rely on potentially classified engineering details. Discrimination requires making a measurement that unambiguously and uniquely identifies the actual warhead, and the objective of many countermeasures approaches is specifically to deny the defense the ability to do this. Thus while it is highly desirable for the defense to gather all available measurement data, doing so does not guarantee that discrimination can be successfully accomplished.

SUMMARY

The potential effectiveness of wide-area exo-atmospheric ballistic missile defenses remains a controversial subject. In particular, because they operate in the vacuum of outer space, such defenses are potentially vulnerable to a wide range of light-weight countermeasures. The issue of how well a defense will be able to discriminate the actual warhead in a countermeasures environment is the central question in the debate over the potential effectiveness of exo-atmospheric defenses. Supporters of such defenses argue that U.S. technological advantages will allow it to defeat any countermeasures that a country like North Korea might be able to develop. Critics point out that, after more than fifty years of developing such defenses, no solution to the countermeasure problem has appeared and that no testing against credible countermeasures appears to be taking place. The secrecy associated with countermeasures and counter-countermeasures will likely make it very difficult to reach any consensus on the potential effectiveness of these defenses.

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