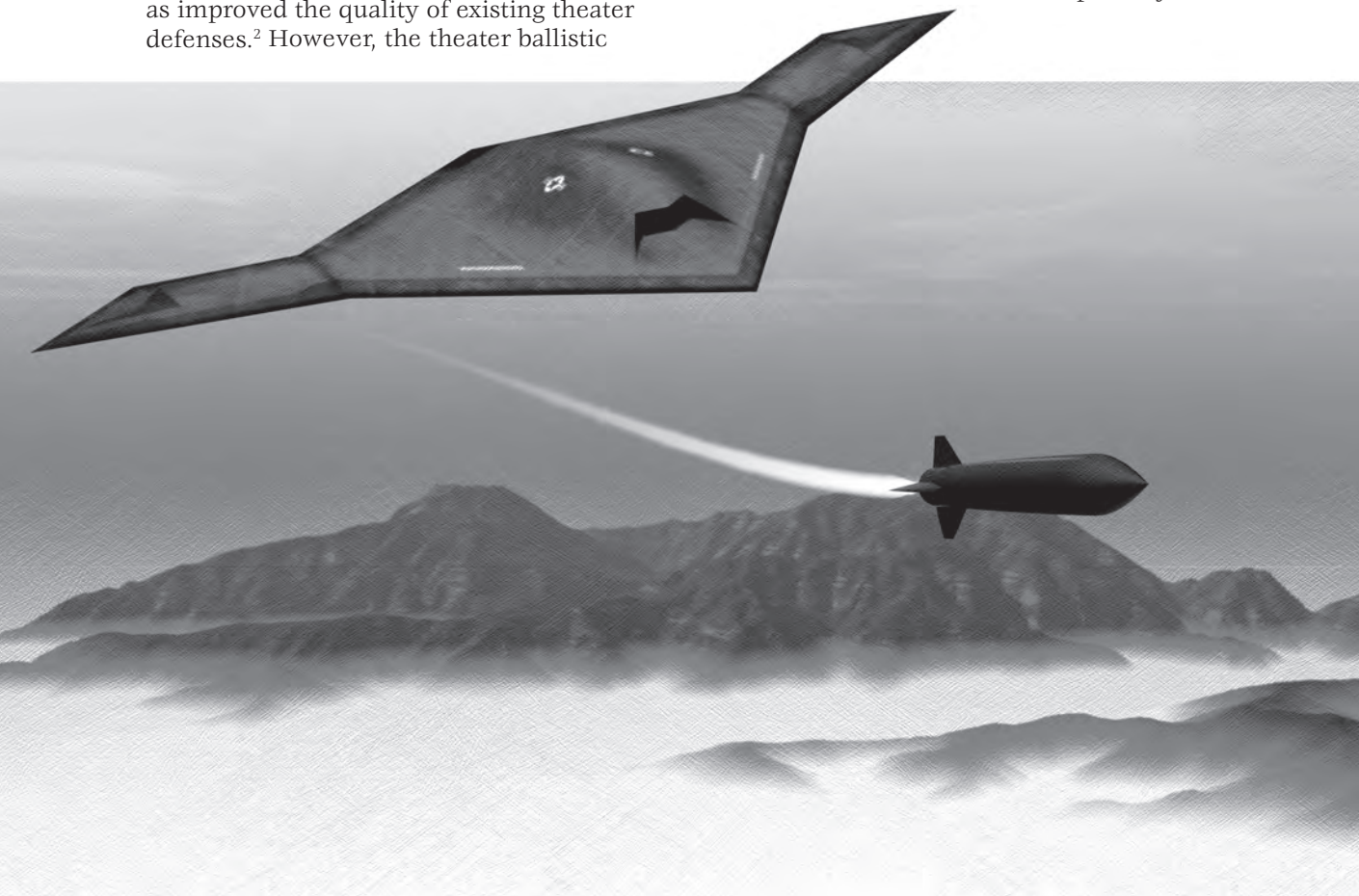
The Role of Airpower in Active Missile Defense

Col Mike Corbett, USAF, Retired
Paul Zarchan

Ballistic missile defense is a contentious issue. Some people consider it an essential tool for modern security; others believe that it diverts critical resources from more pressing needs.[1] Questions have continued to surface ever since the first German V-2 missile fell on Europe in 1944. During Pres. George W. Bush's administration, the military deployed an initial defensive capability against long-range missiles and increased the numbers as well as improved the quality of existing theater defenses.[2] However, the theater ballistic missile (TBM) threat has also changed with the evidence of new, dangerous capabilities on the horizon.[3] Given the new emphasis on capabilities against near-term regional threats, perhaps now is a good time to reexamine the role that airpower might play in this challenging mission area.[4]

What is the proper role of airpower, and what does it bring to active missile defense that surface- and space-based forces do not? Should combat air forces have a primary



role in this mission area? Finally, can we undertake a new mission area without jeopardizing the traditional core capabilities of the combat air forces?

Air-Launched Hit-to-Kill

This article describes a concept that treats ballistic missiles in the same manner as conventional air-breathing threats, using similar doctrine and many of the same technologies employed by today's combat air forces. Known as Air-Launched Hit-to-Kill (ALHK), this concept employs small kinetic interceptors directed to targets by a staring infrared search and track system (IRSTS). Initially fighters would carry the interceptors, but unmanned combat air systems would eventually assume that task as well. ALHK is not a new idea, but we and other individuals in the military, industry, and academia have worked to refine it into the concept presented here. This article argues that airpower enables this distributed operational concept and could enable the engagement of most threat ballistic missiles in the boost, ascent (early midcourse), and terminal phases of their flight.

Performance estimates offered here are based on unclassified threat models and timelines from the American Physical Society's report on boost-phase intercept systems, published in 2004.[5] We used the society's models, incorporating them in a three-degree-of-freedom, three-dimensional, end-to-end simulation of the entire intercept process to generate the results contained herein. This Monte Carlo simulation (i.e., repeated simulation trials that produce statistical performance projections) includes sensor noise; realistic predicted intercept-point errors; and combat-proven guidance and filtering techniques that can be used to hit a target during its boost, ascent, or terminal phase of flight. This engagement simulation is an extension of the one originally presented in a previous work.[6] Our results to date indicate that the ALHK system concept could engage ballistic missiles at their most vulnerable points and, perhaps most importantly, do so in a cost-effective manner.

However, before we examine this concept, we need to take a closer look at the threat. Besides the number of missiles produced and the number of countries that have them, is the threat *really* growing? To date, conventional (nonnuclear) TBMs have never constituted a militarily significant capability that could hold key assets at risk or prevent the attainment of key objectives—although they could penetrate most defenses.[7] A nuclear warhead changes the story, but we could argue that deterrence works pretty well against adversaries with enough capability to develop nuclear weapons. So, is the threat of TBMs really changing?

Indications suggest that it is. Countries such as Iran are building ballistic missile arsenals and equipping them with precision-guidance capability.[8] This is not a tremendous technological jump, given access to the global positioning system or an equivalent system. It becomes just a matter of providing the warheads a means to navigate to their targets, in many ways resembling the way Joint Direct Attack Munitions work. The difference is that, instead of dropping them from an airplane, a TBM "tosses" in its warheads—but the last 15 seconds of flight would be very similar with both using aerodynamic forces to correct navigation errors. We must also consider other guidance methods (antiradiation, laser illumination, etc.) and decide whether any of these could also work with a ballistic-missile delivery system. We believe that at some point, even mobile assets may be at risk to precision attacks delivered by ballistic missiles.

Consequences of an Adversary's Obtaining Precision-Guided Theater Ballistic Missiles

To better understand the importance of precision guidance, we should consider how the German missile attacks on Antwerp could have changed the outcome of a

critical battle during World War II, had such guidance been available. From the fall of 1944 to the spring of 1945, the Allied campaign depended upon an adequate flow of material into Europe, and Antwerp was one of the few ports available. Thwarted by the Allies' air superiority, the Germans turned to V-1 and V-2 weapons to attack the port and slow the flow of Allied logistics.

Over 1,700 V-2s and 4,000 V-1s targeted the Antwerp area during this period although only about 30 percent reached the heart of the city.[9] The attacks killed over 3,700 people, sank one ship, and constricted supply lines yet never put the port out of action. The impact might have proven decisive had the Germans been able to target individual ships, docks, or warehouses when the Battle of the Bulge hung in the balance.

The Thanh Hoa Bridge in Vietnam provides a historical example of the transition to weapons with precision guidance. For over six years, a total of 871 US Air Force sorties dropped unguided bombs on the bridge but failed to close it. However, the first operational application of laser-guided bombs on 13 May 1972 resulted in direct hits on the supporting piers, dropping the center span and closing the bridge.[10] Although the US military has long understood the value of precision attack, to date we have never been threatened by such a strike. Precision-guided TBMs may change that in the near future.

Finally, we should consider an adversary's ability to concentrate his attack at a specific point and time. Timing multiple launches for simultaneous arrival is not difficult, and a sufficient number of ballistic missile launches can overwhelm any surface-based defense. Combining this ability to *mass* the attack (i.e., the simultaneous arrival of many weapons, a capability now possessed by some potential adversaries) with precision guidance would allow an adversary to overwhelm any surface-based defense system and destroy its critical tracking radars. The absence of sensors eliminates a defensive system's ability to intercept ballistic missiles, after which the adversary can deny allied forces access to ports and airfields.

We believe that the threat is really changing in ways that will affect how and where future battles will be fought. This growth in an adversary's capability comes not from mating ballistic delivery systems with weapons of mass destruction but with precision guidance, which, combined with an adversary's ability to attack key locations in mass, may significantly inhibit a future allied force's power projection options.

A Closer Look at the Threat

TBMs are difficult to locate and need not emit any exploitable signals prior to launch. They can be hidden for long periods and then rolled out, erected, and launched without warning. Once the engine fires, the TBM becomes very visible and easily distinguishable from other missiles encountered on the battlefield. Surface-to-air missiles accelerate very quickly, their engines usually burn for less than 20 seconds, and they follow a somewhat erratic path as they guide toward their target.[11] Ballistic missiles, on the other hand, accelerate more slowly and their engines burn much longer. Those with longer range (medium to intercontinental) rise nearly vertically at first, taking as long as a minute to climb through an altitude of 10 kilometers (km). Depending on their size and range, their engines may burn for more than four minutes, and the missiles may have more than one stage. Some reach acceleration levels of 8 g's to 15 g's or more prior to burnout or staging.[12] (See fig. 1 for a simulation of a single-stage generic intermediate range ballistic missile's [IRBM] altitude and acceleration profiles.) It is important to note that part of the axial acceleration of the IRBM appears as a target maneuver to a pursuing interceptor, and the amount of required interceptor acceleration to engage the target is related to the magnitude of this apparent target maneuver.

An interceptor capable of defeating such a threat during the boost phase must be

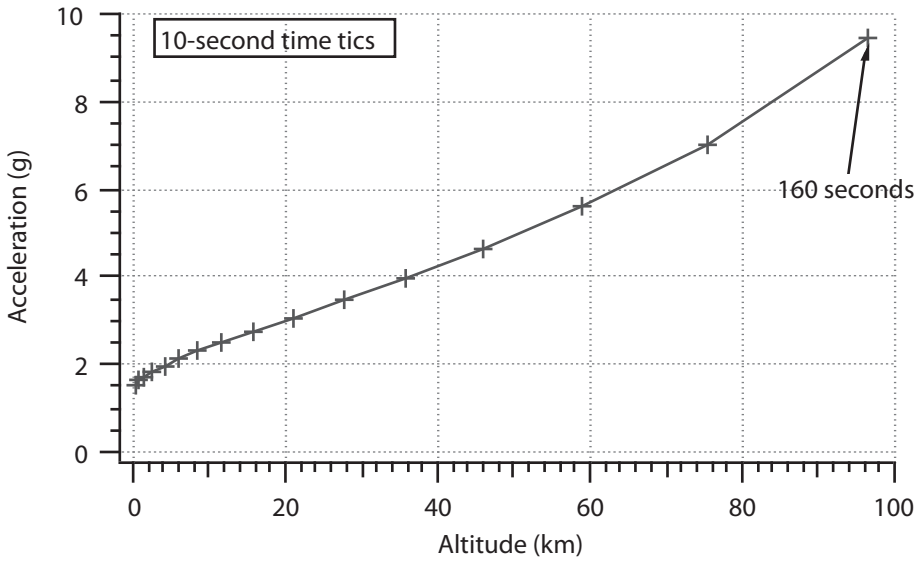


Figure 1. Generic IRBM acceleration as a function of altitude during the boost phase

able to accelerate similarly within the environment where the intercept will occur. Below 35 km, TBM acceleration levels are still relatively low, but they grow quickly as the threat consumes its fuel load. For intercepts above 50 km altitude, TBM accelerations can exceed 5 g's (fig. 1). The required increase in an interceptor's acceleration relative to the threat depends upon the geometry of the engagement and the type of guidance used. Traditional proportional navigation guidance demands that the interceptor have a significant maneuver advantage over the threat (a ratio of three to one or greater). However, we believe that optimized guidance can significantly reduce this maneuver margin, possibly to a fraction of the target's acceleration capability.[13]

After the boost phase, the guided warhead will likely separate from the booster, and defensive countermeasures such as decoys may also deploy. Unless a postboost system applies thrust—either to correct boost-phase navigation errors or compensate for a moving target—the flight path will remain ballistic and highly predictable during this midcourse period. Depending on the range to the target, this ballistic period can last many minutes and give defending aircraft time to respond from regional ground-alert sites. In the case of our generic IRBM (fig. 2), we see that the midcourse phase of flight starts at approximately 200 seconds and ends at approximately 1,050 seconds, indicating that the target's flight path is highly predictable for about 14 minutes.

The terminal phase of a ballistic missile's flight begins when the descending warhead encounters the upper atmosphere at approximately 80 km altitude. Although the air is exceptionally thin at this point, it does exert a drag effect. Heating of heavy pieces begins, and light pieces such as chaff and decoy balloons fall back, each having identifiable signatures. As the descent continues, the atmosphere becomes progressively denser, and these effects increase. Heavy, irregular objects such as fuel tanks begin to tumble and eventually break up. By 30 km altitude, the air is dense enough for the control surfaces on a cone-shaped warhead to effect small maneuvers to compensate for guidance errors or begin target homing. Everything that remains intact during this

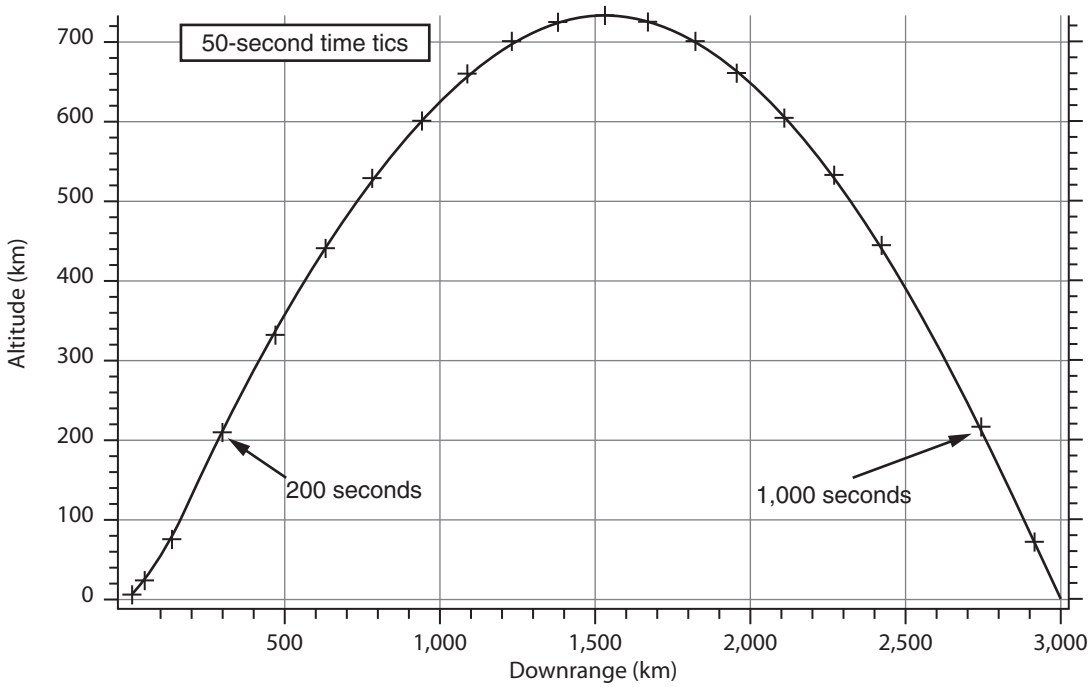


Figure 2. Duration and altitude of a generic IRBM's trajectory during the midcourse phase

period slows and starts to get very hot. By the time a warhead passes 15 km altitude, even the fastest warhead (one that has traveled the longest distance) has slowed to less than five kilometers per second (km/sec) and normally approaches its target from 20 degrees above the horizon or higher. This final descent to the target from 15 km altitude takes about 15 seconds, during which time aerodynamic forces enable the greatest maneuvering potential.[14] A simple computer simulation, in which the ballistic coefficient for several items is treated as a constant, illustrates how these objects (balloons, tank, and reentry vehicle) traveling at 3 km/sec decelerate as they enter the atmosphere (fig. 3).[15] Objects with the most drag (or smallest ballistic coefficient β) have their peak decelerations at the higher altitudes. The figure indicates that the deceleration profiles of all objects are different and that quantities related to the deceleration may serve as useful discriminators.

Although desirable, no single interceptor could engage all threats at any altitude from the surface up. Interceptors designed for engagements in the atmosphere below 35 km altitude can use aerodynamic forces for maneuvering but must cope with higher heating as velocities increase. We refer to these as lower-tier interceptors and show their performance based on a burnout velocity of 1.75 km/sec. Interceptors designed for higher altitudes must use lateral rocket thrust or thrust vectoring for maneuvering, and the complex interaction with missile-body aerodynamics creates adverse problems at altitudes below 50 km. These upper-tier interceptors also need much higher velocities but can avoid heating problems by performing intercepts only above 50 km. We indicate their performance based on a burnout velocity of 3.5 km/sec.

Both upper- and lower-tier interceptors have advantages and disadvantages during the terminal phase of flight. The upper-tier

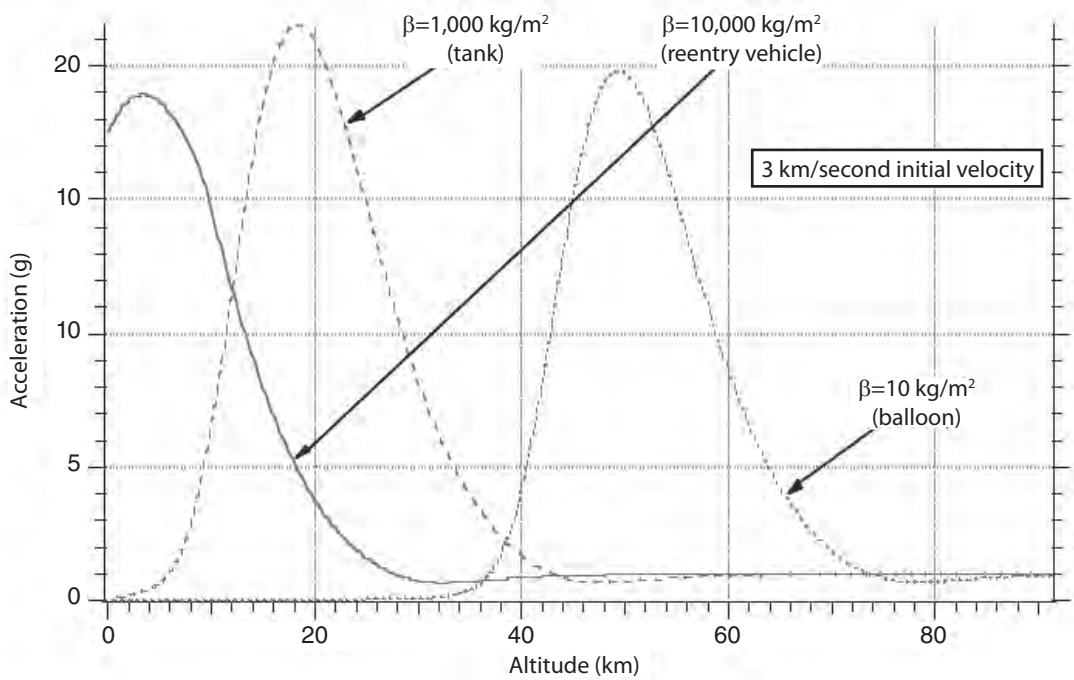


Figure 3. Early peak decelerations for objects with the most drag (or lowest ballistic coefficient)

systems would not have to cope with high deceleration levels, but having the agility needed for upper-tier boost-phase engagements would enable them to maneuver rapidly and intercept warheads as atmospheric interaction revealed the countermeasures. Lower-tier interceptors might have to deal with much higher deceleration levels and might have a very narrow engagement zone, if any, against the longest-range threats. However, a very low minimum-engagement altitude can permit a second shot if the first intercept attempt misses.

What Airpower Can Bring to This Fight

Airpower enables a distributed operational concept that can engage the TBM threat during the boost, ascent (early midcourse), and terminal phases of flight by using common air-launched interceptors and a common aircraft-carried sensor. Airpower applied to missile defense provides more than simply a platform that can get close enough to the launch point to engage in the boost or ascent phase, or respond fast enough from ground alert to engage in the terminal phase.[16] Airpower applied to missile defense allows a commander to focus defensive capability with the same speed and flexibility commonly associated with attack operations. Instead of utilizing a fixed defensive deployment tied to stationary radars, a commander could rapidly establish or reinforce a defensive posture, move aircraft forward to pursue boost or ascent engagements, or cover the movement of surface forces with a combat air patrol providing terminal defense.

In addition, launching an interceptor missile above 12 km altitude has a significant impact on its performance. Although

a supersonic fighter may be traveling only 0.3 km/sec, launching the interceptor missile at an altitude above 90 percent of the atmosphere has the effect of reducing aerodynamic drag on the missile and may add over 1 km/sec to the interceptor's burnout velocity.

For example, based on engagement-simulation results from previous works, a notional 3,000 km IRBM (figs. 4 and 5) launched from northern Iran toward Rome would impact in approximately 17 minutes.[17] Strike or escort aircraft operating within Iran could autonomously detect and engage threatening ballistic missiles during their boost phase. Moreover, combat air patrols operating in eastern Turkey could autonomously detect threats in their boost phase, engage them in their ascent phase, and subsequently pass precise threat-tracking data downstream for follow-on terminal engagements. Assuming nominal times for detecting the launch, issuing the warning, scrambling, and climbing out, fighter aircraft on ground alert at Aviano Air Base, Italy, would have sufficient time to scramble, acquire, and track the threat, and then launch an interceptor for a terminal-phase engage-

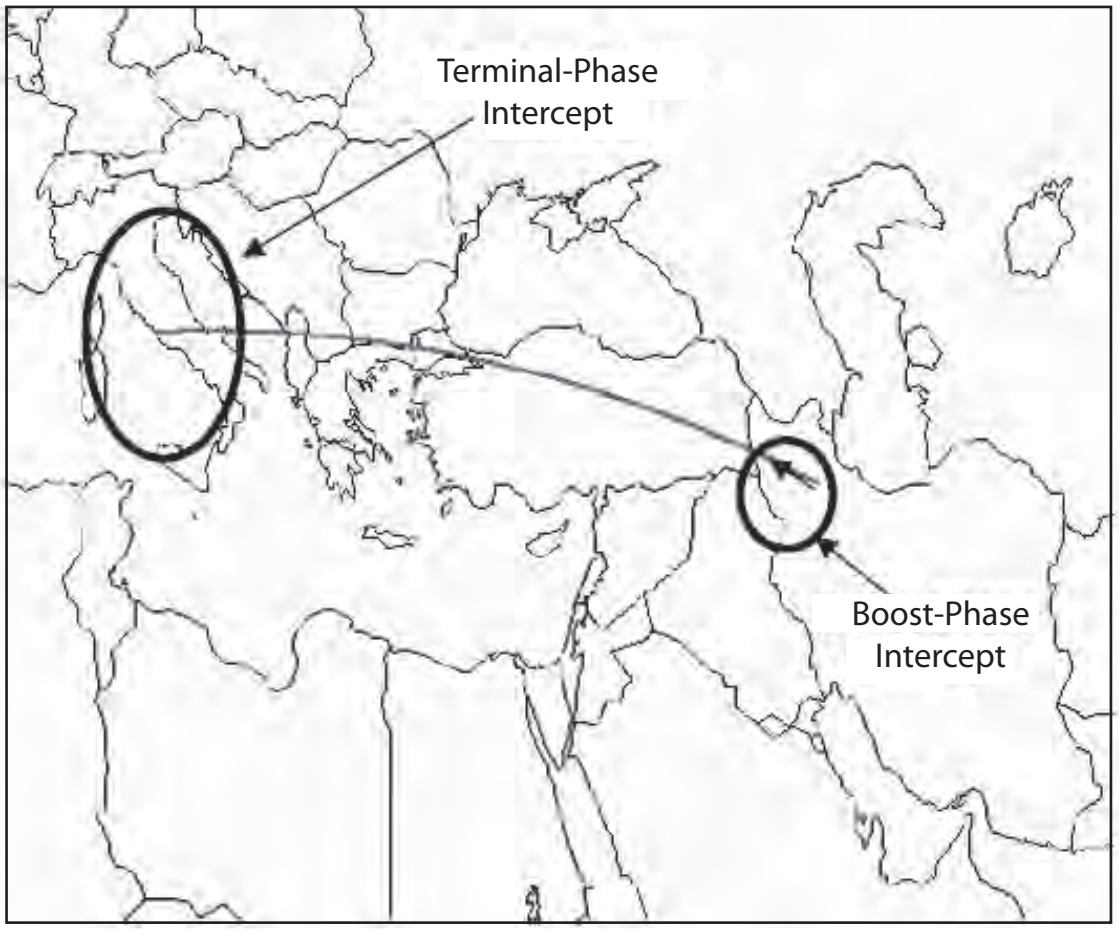


Figure 4. Operational areas for aircraft using a lower-tier interceptor to defend Rome against an IRBM launched from Iran

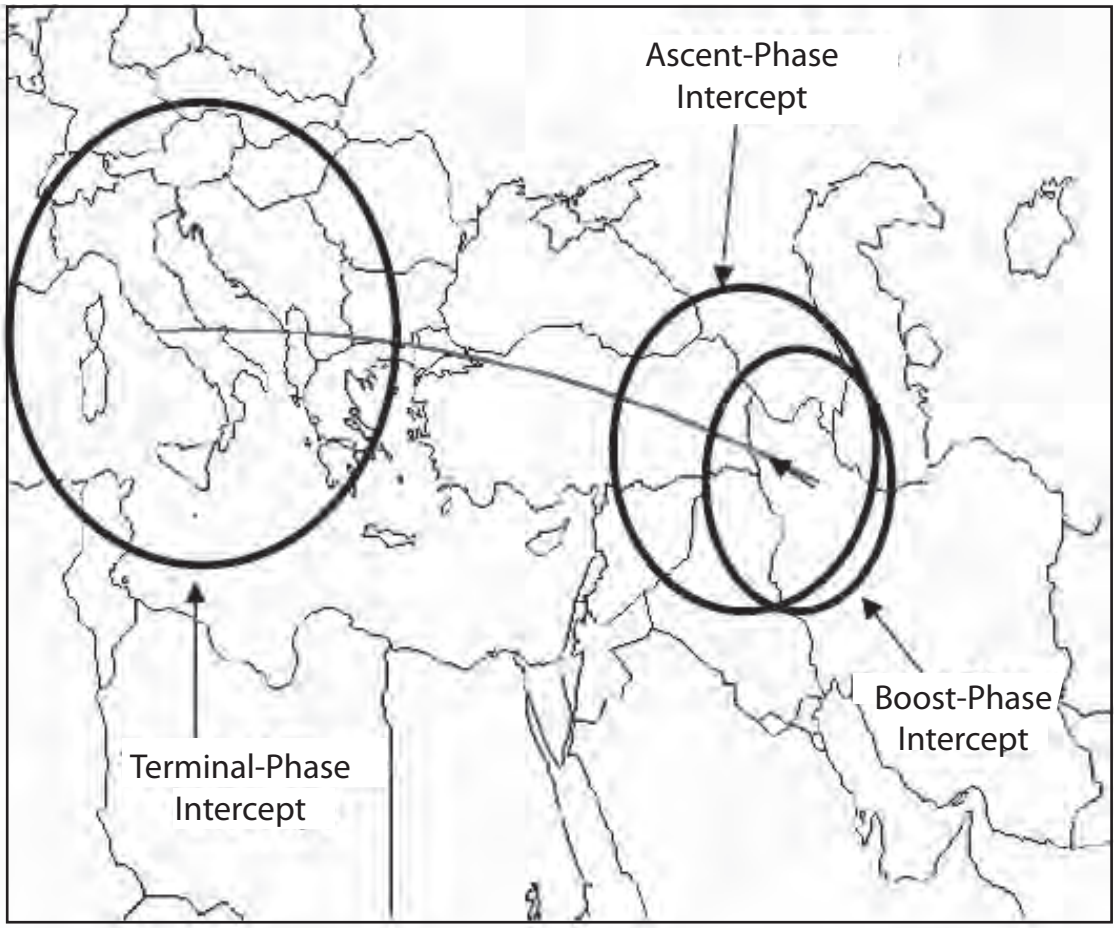


Figure 5. Operational areas for aircraft using an upper-tier interceptor to defend Rome against an IRBM launched from Iran

ment.[18] The two figures represent operational areas for an aircraft defending Rome against an IRBM launched from Iran—figure 4 depicting the capability of a lower-tier interceptor and figure 5 representing the operational area of an upper-tier interceptor. We can see from figure 4 that the lower-tier system will not have ascent-phase capability against this category of threat.

Each aircraft can operate autonomously for boost- or ascent-phase engagements or as part of a network for terminal defense. Aircraft providing defense can be massed at a particular point or distributed over a large area. They can provide terminal defense for a limited time at a port or airfield during deployment of a persistent surface-based system, or they can thin the wave of attacking threats through boost-phase engagements during fighter-sweep operations. Finally, but perhaps most importantly, we base this concept on the development of a small interceptor that should cost less than the threat it will attempt to engage, a characteristic that holds the promise of making airpower-based missile defense a cost-effective concept.

The Air-Launched Weapon

What would these defensive weapons look like? The size of the weapon is directly related to its maximum employment range. The air-launched interceptor must attain a high velocity so that it can quickly close the distance to the predicted intercept point, yet retain the capability to maneuver to the precise target location. It also requires sufficient lateral acceleration to actually hit the target. A lower-tier interceptor may use aerodynamic forces for maneuvering; however, any attempts by an interceptor to engage at ranges greater than 150 km will result in intercepts outside the atmosphere, thus requiring propulsive thrusters so that it could maneuver in response to guidance commands. Because maximum-range engagements in the boost phase require hitting the target near the end of that phase at the target's greatest rate of acceleration, the interceptor must have significant maneuverability. However, we must address two principal areas of technical risk: exoatmospheric maneuverability of the kill vehicle and ascent-/terminal-phase discrimination, discussed later in greater detail.

Lower-Tier Systems

The Net Centric Airborne Defense Element (NCADE) proposed by Raytheon Missile Systems is an interceptor roughly the size of today's advanced medium-range air-to-air missile (AMRAAM). Similar in shape to an AMRAAM, the two-stage NCADE lacks a warhead but has an infrared seeker.[19] The seeker guided on and hit a boost-phase target in December 2007; subsequent testing revealed significant capability in terminal intercepts as well.[20] Due to its large fuel-to-mass ratio, two stages, and very light guidance system, NCADE is potentially several times faster than an AMRAAM.[21] Such speed allows it to close rapidly with a boosting missile, giving it a maximum employment range of about 150 km. However, that range depends upon the threat's aspect, acceleration, and distance into its flight when the interceptor launches.[22] NCADE's proposed design also includes a lateral propulsive capability, which could enable some intercepts well above 35 km altitude.

The Air-Launched Hit-to-Kill concept proposed by Lockheed Martin Missiles and Fire Control uses a Patriot Advanced Capability 3 (PAC-3) missile as the interceptor.[23] Equipped with an active radar seeker similar to the AMRAAM's, the PAC-3 is a larger missile and even faster than NCADE. However, its greater length significantly complicates carrying it aboard aircraft and limits the number of missiles that any one aircraft could accommodate. However, this established missile, currently in production, needs little modification to employ from an aircraft and has an excellent performance record.

Both the NCADE and Air-Launched Hit-to-Kill use the kinetic energy of the intercept as the kill mechanism and do not carry an explosive warhead. Although designing an interceptor without a warhead may seem counterintuitive, the high closure velocities encountered in missile defense complicate proximity fuses and reduce the effectiveness of a blast warhead. Further, the kinetic energy of the interceptor mass at impact exceeds the chemical energy of an equivalent mass of TNT when the closure velocity exceeds 2.9 km/sec.[24]

Upper-Tier Systems

Development of an upper-tier system involves two challenges: (1) building a kinetic-kill vehicle that can meet maneuverability and fuel requirements and (2) developing an aircraft sensor that has the discrimination capability for both ascent- and terminal-phase engagements. Long-range performance requires a larger, faster missile with a kill vehicle capable of enough exoatmospheric maneuvering to hit a target accelerating at 15 g's. Parametric analysis, based on the engagement simulation discussed in other works, indicates that we

should be able to build a 750 kilogram (kg) weapon that could reach a burnout velocity of at least 3.5 km/sec, retain sufficient fuel to accelerate an additional 1.5 km/sec to 2 km/sec (also known as divert velocity), and accelerate laterally at greater than 10 g's, enabling it to hit medium-range, intermediate-range, and intercontinental ballistic missiles.[25] Design constraints on such a weapon would allow it to fit internally into either the F-35 or the Navy's Unmanned Combat Air System—moreover, F-15, F-16, or F-18 aircraft could carry it externally.

Upper-tier systems are expected to engage only above 50 km in altitude, but this is not a hard limit. However, the ability to engage *well above* 50 km expands the boost-phase envelope and provides intercept capability during the ascent phase. The benefit of engaging at altitudes as low as 50 km is much more important for terminal intercepts, during which the atmosphere reduces the effectiveness of countermeasures.

Unfortunately, although we believe that such a system is feasible, no one has yet demonstrated the concept. Considering the complications of insensitive munitions requirements and the Navy's desire to avoid hypergolic liquid fuels, the design challenge becomes even greater.[26] The needed exoatmospheric agility, constrained by these operational requirements, represents the first of two main technical risks for this concept.

Figures 6 and 7 depict sample boost- and ascent-phase operational areas for a 3.5 km/sec interceptor employed against an IRBM from Iran threatening Rome. The small squares depict possible points from which aircraft could successfully engage IRBMs by using a 3.5 km/sec interceptor. Note that for a boost-phase intercept, the launch platform might have to operate in or very close to Iranian airspace. Alternatively, the aircraft's operational area for upper-tier ascent-phase intercepts offers the possibility of operating the launch platform well outside the borders of Iran.

The Aircraft Sensor

ALHK requires a precision tracking capability that will work at ranges out to 1,000 km. Fighter aircraft can climb above clouds rapidly, so a passive infrared sensor becomes a viable alternative to active radar. Infrared sensors will provide angle information only, but those angles are much more precise than the ones measured by radar; furthermore, active ranging data from either the fighter's radar or laser ranging (an optional function built into the infrared sensor) could probably be combined to make this a very precise tracking solution. If extreme range or the target's characteristics make active ranging unavailable, stereo tracking by two sensors separated by roughly 100 km will provide sufficiently accurate track data for boost- and ascent-phase engagements.

Analysis has shown that a staring infrared sensor with an aperture of about 15–20 centimeters could furnish the required performance.[27] That is, the sensor would closely resemble today's Sniper and LITENING targeting pods. In fact, we have demonstrated the Sniper pod's performance by tracking the ground missile defense (GMD) interceptor throughout the entire boost phase from two F-16s over Edwards AFB, California, during the GMD flight test (FTG-05) out of Vandenberg AFB, California, in December 2008.[28]

This IRSTS sensor must do more than just detect and track; it must also assist the interceptor in discriminating between the warhead and other objects, such as decoys—a process that is complicated by natural debris as well as intentional countermeasures. We doubt that either the IRSTS or the interceptor seeker can do this individually; rather, a successful intercept will depend upon a contribution from each one. However, past observations of missile tests by similar systems give us reason to believe that it is possible. This discrimination capability for ascent- and terminal-phase intercepts represents the second of the two primary technical risks for this concept.

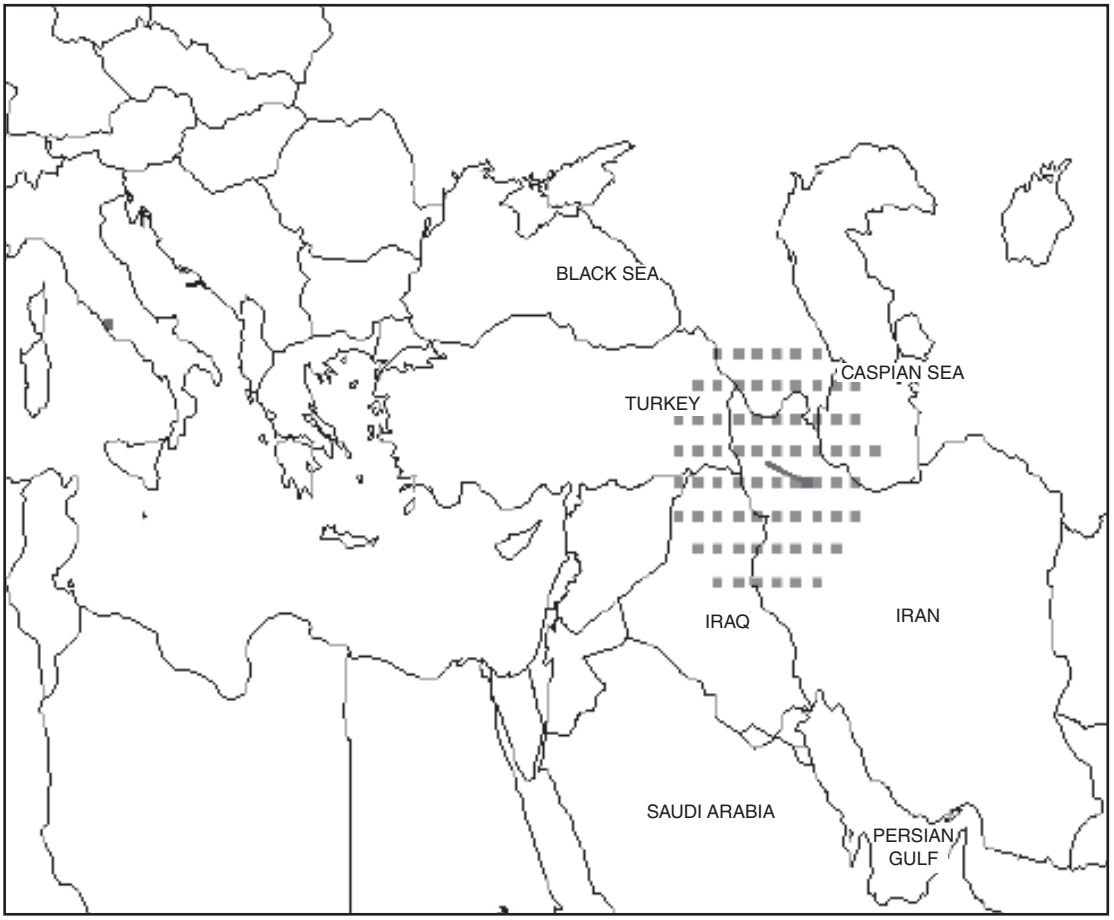


Figure 6. Boost-phase operational area, assuming launch of a 3.5 km/sec interceptor 10 seconds after launch of the IRBM target

Size Matters, but Smaller Is Better

The interesting thing about a missile's cost is its close relationship to the missile's weight. Although it may seem obvious that large ones cost more than small ones, plotting all recent unit production costs for missiles in relation to their weight more clearly defines this—and even suggests a formula. Eugene Fleeman observes that as a first-order design consideration, production cost is a function of weight. That is, $C_{1000} \sim \$6{,}100\ W_L^{0.758}$ where C represents the unit cost of the 1000th missile, and W_L is the weight in pounds.[29] Fleeman's database included only weapons up to 1,500 kg, so extending the formula to 25,000 kg is obviously questionable, but the historical relationship is that small missiles cost far less to produce than big ones. According to his formula, a 500 kg interceptor would cost 5.2 percent of a 25,000 kg interceptor (i.e., a ground-based midcourse defense interceptor); thus, higher production rates are possible, a fact that also drives down unit costs. Lower unit costs make more frequent test-

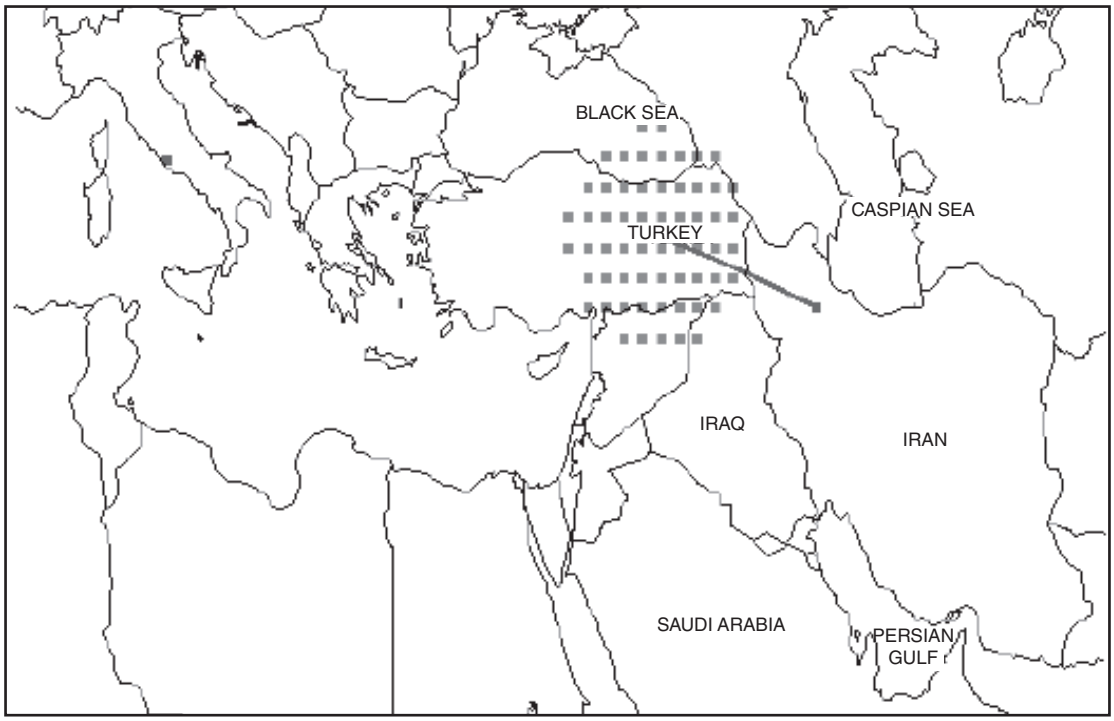


Figure 7. Ascent-phase operational area, assuming launch of a 3.5 km/sec interceptor 80 seconds after detection of the IRBM target and interception of target 270 seconds later (two minutes after IRBM burnout)

ing economically feasible, which in turn drives up confidence in system performance. But airpower provides the delivery platform, thereby enabling the small interceptor and making ALHK possible.

Summary

Many potential adversaries are pursuing precision accuracy in the delivery systems of ballistic missiles. Using combat aircraft to compete head to head with the United States is not a viable option for most opponents, but a ballistic missile provides them an alternative delivery system that could penetrate defenses. We contend that ALHK can defeat IRBM threats in a cost-effective manner. Although we have addressed only IRBM threats, other analysis has shown that ALHK could engage most other ballistic missile threats as well.

A small interceptor launched from a stealthy fighter operating in or near contested airspace can provide the same kinematic performance as a much larger surface-based interceptor launched from well outside that area. In most cases, boost-phase intercepts will require operations in the country where the IRBM launch occurs, thus calling for a low-observable platform. Ascent- and terminal-phase intercepts will not require such platforms and should be compatible with fourth-generation fighters. A staring IRSTS can offer passive detection and tracking for a tiny fraction of the cost of a surface-based radar and could be proliferated throughout the combat air forces of both the United States and its allies. To-

gether, the small interceptor and the staring IRSTS comprise a survivable and highly flexible defensive capability that can frustrate an adversary's planning and even provide additional capabilities well beyond missile defense functions. For example, the military could design the IRSTS to perform long-range detection as well as tracking and identification of air targets, and could design the lower-tier interceptor to engage those targets at very long ranges.

Admittedly, this mission places a new demand on combat aircraft. The mission requirements of ground alert—and, in some cases, airborne persistence—as well as the possible penetration of defended airspace would impose a significant burden on today's combat air forces. In the future, aircraft like the Navy's proposed Unmanned Combat Air System could have mission durations of 100 hours and a very low radar signature, thus addressing both the persistence and penetration requirements.[30] However, even if the Navy pursued initial operational capability (IOC) following the current aircraft-carrier demonstration program, this capability is still more than 10 years away. In the interim, fighters remain the primary option.

Fifth-generation fighters such as the F-35 will bring with them all of the internal-sensor capability necessary to support boost-phase intercepts with both upper- and lower-tier interceptors. Our analysis indicates that the F-35's Distributed Aperture System could immediately detect and track a boosting TBM, in any direction and at any elevation from the aircraft, given a clear line of sight. Fourth-generation fighters equipped with an IRSTS would have ascent- and terminal-phase intercept capability with both interceptors, and IOC for the lower-tier could occur as early as 2015. IOC for the upper-tier interceptor could follow in two to four years, assuming that a technology-development program soon addresses agility requirements.

In 2009 the US Air Force chief of staff and the director of the Missile Defense Agency initiated a joint study of ALHK, which found the concept technically viable and operationally feasible but deferred major decisions until after a detailed cost-benefit analysis could be conducted.[31] To date, although the Air Force has taken the lead on this concept, everyone involved realizes that it will attain full capability only as a joint system. The additional contribution of carrier-based aviation with ALHK could offer enhanced defensive flexibility to a joint force commander, as well as even greater uncertainty to adversaries.

However, as with any new capability, ALHK comes with a significant price tag. Opportunity costs and the impact on combat flight operations demand thorough evaluation in conjunction with an examination of possible enemy countermeasures. We must model the resulting capability in a variety of future campaigns that consider a number of potential technology developments by adversaries, and we must critically assess it before making an acquisition decision. However, as we ponder whether to pursue this mission for the combat air forces, we also need to consider the long-term ramifications if we do not. ✪

Notes

1. 1st Lt Alexi A. LeFevre, "A Strategic Conversation about National Missile Defense," *Strategic Studies Quarterly* 2, no. 4 (Winter 2008): 117, http://www.au.af.mil/au/ssq/2008/Winter/lefevre.pdf; and Jeff Sessions, "Ballistic Missile Defense: A National Priority," *Strategic Studies Quarterly* 2, no. 2 (Summer 2008): 22–30, http://www.au.af.mil/au/ssq/2008/Summer/sessions.pdf.

2. Department of Defense, *Ballistic Missile Defense Review Report* (Washington DC: United States

Department of Defense, February 2010), 15–19, http://www.defense.gov/bmdr/BMDR%20as%20of%2026JAN10%200630_for%20web.pdf.

3. George Jahn, "IAEA Fears Iran Making a Warhead," Associated Press, 19 February 2010, http://www.boston.com/news/world/asia/articles/2010/02/19/iaea_fears_iran_making_a_warhead/.

4. Department of Defense, *Ballistic Missile Defense Review Report*, i.

5. David K. Barton et al., *Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues* (College Park, MD: American Physical Society, 5 October 2004), http://rmp.aps.org/pdf/RMP/v76/i3/pS1_1.

6. See Paul Zarchan, *Tactical and Strategic Missile Guidance*, 5th ed. (Reston, VA: American Institute of Aeronautics and Astronautics, 2007), 721–68.

7. Thomas A. Keaney and Eliot A. Cohen, *Gulf War Air Power Survey: Summary Report* (Washington, DC: US Government Printing Office, 1993), 177, 179; and Freeman J. Dyson, *Disturbing the Universe* (New York: Harper & Row, 1979), 108, http://books.google.com/books?id=RHzoMeU2bxsC&pg=PA108#PPA108,M1.

8. Mohammad-Ali Massoumnia, *Q-Guidance in Rotating Coordinates*, AIAA-91-2784-CP (Reston, VA: American Institute of Aeronautics and Astronautics, 1991). This paper, written by a faculty member of the Department of Electrical Engineering, Sharif University of Technology, Tehran, Iran, indicates that Iranians are familiar with ICBM precision-guidance techniques and are investigating their application to short-range missiles.

9. Gregory P. Kennedy, *Rockets, Missiles, and Spacecraft of the National Air and Space Museum* (Washington, DC: Smithsonian Institution Press, 1983), 20–23.

10. Eugene L. Fleeman, "Technologies for Future Precision Strike Missile Systems: Introduction/Overview," in North Atlantic Treaty Organization, Research and Technology Organization, *Technologies for Future Precision Strike Missile Systems*, RTO Lecture Series, no. 221 (Neuilly-sur-Seine Cedex, France: North Atlantic Treaty Organization, Research and Technology Organization, 2000), http://handle.dtic.mil/100.2/ADA387602.

11. A Google search of "tactical surface to air missile burn times" yields a sampling of many tactical missiles, all of which have burn times of less than 20 seconds.

12. Peter J. Mantle, *The Missile Defense Equation: Factors for Decision Making* (Reston, VA: American Institute of Aeronautics and Astronautics, 2004), 85–92.

13. Zarchan, *Tactical and Strategic Missile Guidance*, 143–61.

14. Mantle, *Missile Defense Equation*, 371–81.

15. The simulation is based on Zarchan, *Tactical and Strategic Missile Guidance*, 721–68.

16. Dean A. Wilkening, "Airborne Boost-Phase Ballistic Missile Defense," *Science and Global Security* 12 (June 2004): 2, http://www.princeton.edu/sgs/publications/sgs/pdf/12_1-2_wilkening.pdf.

17. Zarchan, *Tactical and Strategic Missile Guidance*, 721–55.

18. Thomas H. Kean et al., *The 9/11 Commission Report: Final Report of the National Commission on Terrorist Attacks upon the United States* (Washington, DC: US Government Printing Office, 2004), 20–27, http://govinfo.library.unt.edu/911/report/911Report.pdf. This document discusses the response times for fighters scrambled during the terrorist attacks of 11 September 2001 (9/11). Although the open literature refers to an immediate readiness posture of 15 minutes, alert fighters typically do much better. On 9/11 the fighters from Otis Air National Guard Base, MA, were airborne in seven minutes, and the fighters from Langley AFB, VA, were airborne in six minutes.

19. Michael Leal and Philip Pagliara, "NCADE: Air Launched Boost Phase Intercept Demonstrated" (paper presented at the 2008 Multinational Ballistic Missile Defense Conference, Honolulu, HI, 10 September 2008), 3. (This document is available to the public from Raytheon.)

20. Ibid., 8–12.

21. Ibid., 3.

22. Ibid., 7.

23. "Patriot PAC-3[/ALHK]," *Deagel.com*, http://www.deagel.com/Anti-Ballistic-Missiles/Patriot-PAC-3_a001152003.aspx.

24. Barton, *Report of the American Physical Society Study Group*, 242. This document discusses the actual lethality necessary to defeat a warhead. For the comparison of kinetic energy to chemical energy, see Richard A. Muller, *Physics for Future Presidents: The Science behind the Headlines* (New York: W. W. Norton & Co., 2008), chap. 1. TNT has a chemical energy of 4.18 kilojoules per kilogram. The kinetic energy equation (1/2 mass times the velocity squared) shows that one kilogram of interceptor mass yields 4.18 kilojoules of energy when the closure velocity is 2.9 km/sec.

25. Zarchan, *Tactical and Strategic Missile Guidance*, 291–316.

26. Ashton Carter, undersecretary of defense for acquisition, technology and logistics, to secretaries of the military departments et al., memorandum, subject: Joint Insensitive Munitions Test Standards and Compliance Assessment, 1 February 2010.

27. Barton, *Report of the American Physical Society Study Group*, 192–97.

28. Three F-16s of the 416th Test Flight Squadron, Edwards AFB, CA, flew under contract to the Director, Advanced Technology Weapons, Missile Defense Agency, on 5 December 2008, observing the launch and entire boost phase of the ground-based midcourse defense interceptor out of Vandenberg AFB, CA, with Sniper targeting pods.

29. Eugene Fleeman, *Tactical Missile Design*, 2d ed. (Reston, VA: American Institute of Aeronautics and Astronautics, 2006), 286.

30. Thomas P. Ehrhard and Robert O. Work, *Range, Persistence, Stealth, and Networking: The Case for a Carrier-Based Unmanned Combat Air System* (Washington, DC: Center for Strategic and Budgetary Assessments, 2008), http://www.csbaonline.org/4Publications/PubLibrary/R.20080618.Range_Persistence_/R.20080618.Range_Persistence_.pdf.

31. Marina Malenic, "Companies Await MDA Verdict on Air-Launched Hit-to-Kill Programs," *Defense Daily*, 20 August 2009, http://findarticles.com/p/articles/mi_6712/is_36_243/ai_n35676077/; and "DOD News Briefing with David Altwegg on Fiscal Year 2011 Budget for Missile Defense Agency," *Global Security.org*, 1 February 2010, http://www.globalsecurity.org/space/library/news/2010/space-100201-dod01.htm.

Col Mike Corbett, USAF, Retired

Colonel Corbett (BS, Oregon State University; MS, Purdue University; MS, Auburn University–Montgomery) was the Missile Defense Agency's (MDA) director for advanced technology weapons from 2006 through 2009, leading a small staff in support of kinetic- and directed-energy technology development for advanced ballistic missile defense systems. He led the Air-Launched Hit-to-Kill concept development and the feasibility and engineering assessment of integrating PAC-3-derived interceptors with fighter aircraft. He also led the MDA's evaluation of the Net-Centric Airborne Defense Element, a congressionally directed program to develop a new missile defense interceptor using an existing air-to-air missile seeker. Colonel Corbett joined the MDA in 2005 following his retirement from the Air Force. His military experience included command positions at various levels within Air Combat Command and the Air National Guard, and over 5,000 hours in a variety of aircraft, predominantly fighters.

Paul Zarchan

Mr. Zarchan (BSEE, City College of New York; MSEE, Columbia University) has more than 40 years of experience designing, analyzing, and evaluating missile-guidance systems. He has worked as principal engineer for Raytheon Missile Systems Division, has served as senior research engineer with the Israel Ministry of Defense, and was a principal member of the technical staff for C. S. Draper Laboratory. Currently a member of the technical staff at MIT Lincoln Laboratory, Mr. Zarchan is working on problems related to missile defense. He is the author of *Tactical and Strategic Missile Guidance*, fifth edition, an American Institute of Aeronautics and Astronautics (AIAA) text, and coauthor of *Fundamentals of Kalman Filtering: A Practical Approach*, third edition, another AIAA text. Mr. Zarchan is associate editor of the *Journal of Guidance, Control and Dynamics*.

The conclusions and opinions expressed in this document are those of the author cultivated in the freedom of expression, academic environment of Air University. They do not reflect the official position of the U.S. Government, Department of Defense, the United States Air Force or the Air University.