Arming the Heavens: A Preliminary Assessment of the Potential Cost and Cost-Effectiveness of Space-Based Weapons

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Thinking Smarter About Defense

Center for Strategic and Budgetary Assessments

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Executive Summary

The United States is the world's greatest economic and military power. Perhaps nothing demonstrates the extent of that dominance today better than the country's preeminent role in space. The United States operates by far the most capable and costly network of satellites in the world. Its extensive access to space provides significant economic benefits. It also gives the US military a critical edge over potential adversaries. The combination of US dominance in, and dependence on, space assets has led to both growing concerns about the vulnerability of those assets and calls for the United States to exploit further its existing advantages in space capabilities.

While space has been militarized for many years, it has not, at least as far as can be determined from unclassified sources, been weaponized. In other words, satellites have been used to provide intelligence, targeting and other support to terrestrial-based forces and weapons. However, to date, no country appears to have actually stationed weapons in space. Some analysts believe that the weaponization of space is inevitable and that the United States can and should move rapidly to acquire and field a range of space-based weapons. Others argue that the United States has more to lose than any other country if space is weaponized and that taking steps in this direction would lead to the worst of both worlds—yielding little or nothing in terms of military advantage, and sparking or accelerating an arms race in space that the United States should, instead, be seeking to avert or, at least, delay as long as possible.

Space-based weapons could, in theory, be used to carry out at least four different missions. Specifically, they could be used to:

- defend against ballistic missile strikes;
- attack terrestrial-based (i.e., surface-based and airborne) targets;

- destroy or disable enemy satellites; and

- protect US satellites, by intercepting enemy anti-satellite (ASAT) weapons.

The wisdom and feasibility of acquiring and deploying one or more of these kinds of space-based weapons can only be determined through an analysis that takes into account a broad range of strategic, operational, technological, political, and financial considerations. Of all of these factors, historically, the area that has received the least attention has been the financial costs—specifically, the funding requirements—that would be associated with the acquisition and support of space-based weapons.

This is understandable to some extent. Weapon system cost estimates can only be as accurate as the quality of information available concerning the system's technical characteristics, overall system architecture and operational concept. In the case of space-based weapons, the quality of such information is typically poor. On the other hand, an analysis of space weapons that does not consider the system's budgetary requirements is, at best, incomplete and, at worst, provides a misleading picture of the system's potential cost-effectiveness.

In an effort to raise the level of debate concerning the wisdom and value of acquiring and deploying one or more of the four types of space-based weapons noted above, this report provides rough, order-of-magnitude, estimates of the potential cost of acquiring and supporting such systems. Based on the cost estimates identified or derived in this report, and existing unclassified assessments of potential system effectiveness, this report also offers a range of tentative and preliminary conclusions concerning the likely cost-effectiveness of various types of space-based weapons.

This analysis, which focuses on the potential for deploying space-based weapons over the next 20 years, suggests five broad observations and conclusions:

- First, a constellation of space-based weapons designed to defend the United States against an attack with intercontinental ballistic missiles (ICBMs) would be extremely costly to acquire and support. Moreover, at least based on the technology likely to be available over the next twenty years, such a system would probably not prove to be a cost-effective investment, especially when measured against the cost to a potential adversary of defeating such a system.

- Second, while space-based weapons intended to strike terrestrial-based targets could, in some cases, cost substantially less to acquire and support than space-based ballistic missile defense systems, such weapons would likely prove more costly—and, in some instances, far more costly—than comparably effective terrestrial-based alternatives.

- Third, while space-based ASAT weapons would also generally be less costly to acquire and support than space-based ballistic missile defense systems, there does not appear to be a compelling need, on either cost or effectiveness grounds, to acquire a dedicated space-based ASAT capability—in part, because the US military already possesses or is acquiring a range of terrestrial-based weapons with significant inherent ASAT capabilities.

- Fourth, space-based defensive ("bodyguard") satellites would, to a great extent, be indistinguishable from space-based ASAT weapons. Thus, such systems would likely have similar costs. In addition, their deployment would presumably have similar implications for sparking or accelerating an arms race in space. These weapons would also be incapable of protecting against some of the ASAT threats most likely to emerge in coming years. A more effective and cost-effective approach might be to rely on a range of passive countermeasures. Strengthening US space surveillance and tracking capabilities could also offer an important means of improving the security of US satellites.

- Fifth, although space-based weapons designed to strike terrestrial-based targets, conduct ASAT attacks, or intercept enemy ASAT weapons appear to be neither necessary, nor, generally, as cost-effective as terrestrial-based alternatives, in a few instances—unlike space-based ballistic missile defense systems—they appear to be relatively affordable and may even represent cost-effective options. In these cases, non-budgetary considerations, such the perceived strategic importance of the capability and the potential arms race implications of moving ahead with such a system, will have to play the dominant role in shaping programmatic and policy choices.

The following discussion provides a more in-depth summary of this report's findings concerning each of the four types of space-based weapons that the US military might consider acquiring and deploying over the next two decades.

Space-Based Ballistic Missile Defense Systems

Two types of space-based weapons could be used in the ballistic missile defense role: space-based kinetic-energy interceptors (SBIs), which would destroy or disable their target by hitting it with a high-speed projectile, or space-based laser (SBL) weapons, which would use a beam of electromagnetic radiation to kill their target.

Based on the best available open-source descriptions of potential SBI and SBL systems—provided by the Congressional Budget Office (CBO), the Department of Defense (DoD), RAND, the American Physical Society (APS), and others—this report estimates that an SBI constellation intended for the boost-phase ballistic missile defense mission would have 20-year lifecycle costs of some $29–290 billion, with the lower-end estimate requiring a technological leap in kill vehicle miniaturization. The technological uncertainty and risk associated with developing an SBL system for this mission is far greater. Indeed, it may be doubtful that, even absent budgetary constraints, such a system could be developed within the time frame considered in this report. But assuming those hurdles could be overcome eventually, such a system might have costs ranging from $128–196 billion.

Despite these high costs, it appears that neither of these systems would have more than, at best, a very modest capability, even in the absence of countermeasures. In the case of the SBI constellations considered in this report, if the attacker prudently timed and salvo-launched its attack, only a single intercontinental-ballistic missile (ICBM) could be intercepted (assuming, consistent with current Missile Defense Agency doctrine, that two interceptors would be launched against each booster)—even if the technology worked perfectly. The SBL missile defense constellations considered in this report would also likely have only relatively limited capabilities—e.g., the ability to intercept perhaps half a dozen ICBMs in the event of such an attack.

Since, for a country that has already developed and deployed a single ICBM, the production costs for additional ICBMs would likely be in only the tens of millions of dollars, a simple cost-exchange analysis strongly suggests that the acquisition of space-based ballistic missile defenses would not be a cost-effective option for the United States—at least over the next two decades. Moreover, if the attacker employs even relatively simple countermeasures, the effectiveness of these systems could be substantially further reduced, or eliminated entirely. Furthermore, the cost-exchange ratio appears to be so lopsided in favor of the attacker that this may be a case where the United States cannot prevail by simply outspending its opponent.

Nor are budgetary costs the only obstacle standing in the way of space-based ballistic missile defenses. Especially in the case of an SBL defense, successfully developing a system with even very modest capabilities would require significant technological advances that may not be achievable over the next two decades.

In any event, the United States already possesses a limited surfaced-based ballistic missile defense system, and is developing, or could develop, a number of alternative surface-based and airborne ballistic missile defense systems (e.g., the airborne laser, or ABL). The estimated life-cycle cost of these systems ranges from about $15 billion to $80 billion. This is generally less, and in most cases far less, than the costs projected for the SBI and, especially, the SBL ballistic missile defense systems considered in this report.

Although generally less costly, as with space-based ballistic missile defense systems, serious questions exist about the likely effectiveness, and thus cost-effectiveness, of terrestrial-based ballistic missile defense options. In other words, it is possible that a cost-exchange analysis of these terrestrial-based options for ballistic missile defense would also reveal a significant—and perhaps insurmountable—advantage resting with the offense. On the other hand, it is possible that, while space-based defenses may not represent a cost-effective option (at least over the period considered in this report), one or more of the terrestrial-based alternatives that the US military is, or could, be, pursuing may represent a cost-effective means of countering some types of ballistic missile threats.

Space-Based Systems for Attacking Terrestrial Targets

A space-based kinetic-energy weapon designed to strike terrestrial targets could be developed and deployed for far less than it would cost to acquire a space-based kinetic-energy weapon (i.e., an SBI) designed for boost-phase ballistic missile defense—in part because the size of the constellation required would be much smaller. However, such a system would still likely be substantially more expensive than comparably-effective surfaced-based alternative prompt-strike systems—such as a force of ICBMs or submarine-launched ballistic missiles (SLBMs) equipped with a maneuverable reentry vehicle (i.e., a common aero vehicle, or CAV) armed with conventional munitions. As in the case of the ballistic missile defense mission, the need to place space-based weapons into orbit tends to substantially increase the cost of such systems, relative to terrestrial-based alternatives.

In general, SBLs designed for this mission would be even more technologically risky and less cost-effective than space-based kinetic-energy systems. An SBL constellation designed to strike terrestrial-based targets might cost as much as one intended for boost-phase ballistic missile defense (i.e., $128–196 billion), depending (among other things) on the desired response time (which would largely drive the size of the constellation required). Moreover, such a space-based system would be capable of attacking only a narrow class of relatively soft targets. An SBL system designed essentially to harass, rather than disable or destroy, an even smaller class of targets (e.g., to illuminate an aircraft's canopy in order to degrade the pilot's view) could be acquired at lower cost, but its capabilities would be much more limited.

It is also unclear how critical the prompt-strike mission is for the US military—whether carried out by space-based or terrestrial-based systems. For targets not requiring prompt strike, aircraft equipped with precision-guided munitions (PGMs) would appear to represent a far more cost-effective option for the United States.

Taken together, these findings suggest that, at present, the prompt-strike mission does not provide a convincing rationale for developing and deploying space-based weapons. That said, in contrast to the case with space-based ballistic missile defense systems, it is much more difficult to dismiss space-based weapons designed to attack terrestrial targets on simple affordability and cost-effectiveness grounds.

For a variety of reasons—including the availability of comparably effective and less expensive surface-based alternatives, as well as concerns about sparking, or at least accelerating, an arms race in space that would run counter to US interests—it may make little sense for the US military to acquire space-based weapons for the foreseeable future. However, while developing and deploying a space-based CAV system, for example, would (at some $12 billion) be more costly than acquiring a surface-based CAV system (at $4 billion, or less), it would certainly be affordable for the United States.

And, in contrast to the case with space-based ballistic missile defenses (which may not only be less cost-effective than terrestrial-based alternative systems, but appear likely to fail the cost-effectiveness test when measured against an opponent's ability to overwhelm such a defense), a space-based prompt-strike system—even if not generally the *most* cost-effective approach—might still prove to be *a* cost-effective means of attacking some high-value targets.

Space-Based ASAT Systems

As is the case with space-based prompt-strike capabilities, a space-based ASAT capability could be acquired at far less cost than a space-based ballistic missile defense system of even very limited effectiveness—again, in part because far fewer systems might be required in such a constellation. As in the case of space-based strike systems, however, it also appears that there are terrestrial-based alternative systems that could provide comparable ASAT capabilities and, in most cases, provide these capabilities at lower cost.

Although generally more expensive than terrestrial-based systems, the cost of space-based ASAT capabilities could vary substantially, depending, among other things, on the specific architecture and capabilities of the space-based system and the number of satellites to be targeted. SBIs and SBLs intended for use in an ASAT role would not generally need to be as capable as SBIs and SBLs designed for the boost-phase ballistic missile defense mission. Thus, it should be possible to keep costs lower. However, the costs could still be very high, perhaps in the tens of billions of dollars or more. At the other extreme, the acquisition of simple "space mines" might be relatively inexpensive.

Terrestrial-based ASAT systems would generally be less costly to acquire, particularly in terms of marginal costs. In the case of the United States, this is especially true, because the US military already possesses or is developing a wide range of terrestrial-based systems that have substantial inherent ASAT capabilities. These include surface-based midcourse ballistic missile defenses, ICBMs and other ballistic missiles, and the ABL. Modifying these systems for the ASAT mission would be relatively simple and inexpensive.

The United States, Russia and China have each developed and tested ASAT systems. Most recently, in January 2007, China tested a ground-based kinetic-energy interceptor, successfully intercepting an aging Chinese weather satellite stationed in low-earth orbit. However, only Russia appears to currently possess a dedicated ASAT interceptor capability—a relatively primitive "co-orbital" system—and it is unclear whether this system is still active. A range of other countries possess a much more limited inherent ASAT capability, primarily in the form of short- and medium-range ballistic missiles that could be modified for ASAT use—although, turning this inherent capability into an actual, effective capability could be difficult for some of these states. If a country also has nuclear weapons, its inherent ASAT capability would be significantly greater.

As with ballistic missile defenses and prompt-strike systems, the effectiveness and cost-effectiveness of ASAT weapons—whether space- or terrestrial-based—could be substantially, and perhaps dramatically, reduced through the use of various countermeasures. Possible ASAT countermeasures include satellite hardening and the use of decoys. On the other hand, some types of satellites might be difficult to protect, especially large, costly and complex satellites stationed in low-earth orbit.

Taken together, these findings suggest that, even assuming the United States would benefit from the acquisition of a significant ASAT capability, there may be no need—at least for the foreseeable future—for the US military to develop and deploy *space-based* ASAT systems.

Moreover, relying on its existing force of dedicated ground-based satellite jammers and ASAT capabilities inherent in terrestrial-based systems like midcourse ballistic missile defenses and ICBMs (rather than developing, testing and deploying dedicated space-based ASAT systems) might help minimize the visibility and provocativeness of the US military's ASAT capabilities. In turn, this could help prevent, or at least defer, an ASAT arms race that it would be very much in the interest of the United States to avoid—because of the unmatched size, effectiveness and cost of its network of satellites, and its greater dependence on those capabilities relative to potential adversaries.

On the other hand, as with space-based prompt-strike capabilities—and in contrast to the case with space-based ballistic missile defense systems—it is difficult to dismiss space-based ASATs on simple affordability and cost-effectiveness grounds. Space-based ASATs may be unnecessary and, in most cases, more costly than comparably-capable terrestrial-based systems, but they are not clearly unaffordable. Indeed, in some cases, such as simple space mines, these weapons could have relatively modest costs.

Using Space-Based Weapons to Protect US Satellite Capabilities

Another possible mission for space-based weapons would be to protect US satellites. In this case, "bodyguard" satellites would be used to destroy or disable various enemy ASAT capabilities. The interplay between ASAT technologies and techniques and defensive satellite capabilities is complex. There is also a dearth of both unclassified analyses concerning what a constellation of bodyguard satellites might look like and reliable, unclassified data concerning the cost and effectiveness of various passive ASAT countermeasures. As a result, it is difficult to provide cost estimates for various, illustrative constellations of bodyguard satellites, or various passive ASAT countermeasures.

Nevertheless, based on the evidence that is available, it is possible to reach a number of conclusions. First, bodyguard satellites would probably have, at best, only very limited capabilities against some of the simplest, as well as potentially most dangerous, ASAT threats likely to emerge in coming years, including space mines and ground-based interceptors armed with nuclear warheads.

Second, space-based kinetic-energy weapons that successfully intercepted enemy space mines would create debris that might itself destroy or damage the very satellite the bodyguard satellite was attempting to protect.

Third, the capabilities of bodyguard satellites would in many (if not most) cases be essentially indistinguishable from those of ASATs. As such, US acquisition of "defensive" bodyguard satellites could have similar consequences in terms of escalating national rivalries and competition in space, in ways that might diminish the overall security of the United States.

Fourth, passive countermeasures could substantially reduce the effectiveness of enemy ASAT capabilities, especially if a combination of different countermeasures were used. The effectiveness, and cost-effectiveness, of particular countermeasures or combinations of countermeasures is difficult to assess with any precision based on open source literature, and much would depend on the specific design of the ASAT and the countermeasures being employed. Nevertheless, a few generalizations can reasonably be made.

One such generalization is that, as with ballistic missile defense systems, in many cases there is a significant difference between the level of effectiveness an ASAT can (in theory) achieve in the absence of countermeasures, and what (in practice) it is likely to achieve if even relatively simple and inexpensive countermeasures are employed.

It is also true that, in general, the cost and effectiveness of the ASAT countermeasures a country would have to develop and deploy to effectively protect its satellites would depend, in large part, on the extent and sophistication of the space surveillance and related capabilities possessed by both the country itself and the adversary thought to pose a threat. Thus, even relatively simple and inexpensive countermeasures might provide US satellites a high level of protection against the kinds ASAT capabilities likely to be acquired by a country like Iran or North Korea, or even—at least for some time to come—China.

In addition, in contrast to the case with space-based ballistic missile defenses, where the advantages accruing to the attacker appear so substantial that it may be impossible for the US military to prevail by simply outspending its opponent, it is possible that the ability to draw on superior resources could have a telling effect in the case of passive ASAT countermeasures.

Taken together, these findings do not provide a compelling case for developing and deploying bodyguard satellites over the next two decades. Indeed, the available evidence suggests that employing a range of passive countermeasures may prove to be a more cost-effective means of protecting US satellite capabilities. On the other hand, as with space-based prompt-strike and ASAT capabilities—and in contrast to the case with space-based ballistic missile defense systems—it is difficult to dismiss bodyguard satellites on simple affordability and effectiveness grounds.

There may be at least some instances in which bodyguard satellites could prove both effective and cost-effective. It is less clear if there are many situations in which bodyguard satellites would prove more cost-effective than passive countermeasures, or whether—even to the extent such circumstances exist—it would make sense to acquire and deploy such satellites, given the possibility that doing so would spark or accelerate an arms race in space that might, ultimately, seriously undermine US interests.

Introduction

The United States is the world's greatest economic and military power. Perhaps nothing demonstrates the extent of that dominance today better than the country's preeminent role in space. The United States operates by far the most capable and costly network of satellites in the world. Its extensive access to space provides significant economic benefits. It also gives the US military a critical edge over potential adversaries. The combination of US dominance in, and dependence on, space assets has led to both growing concerns about the vulnerability of those assets and calls for the United States to exploit further its existing advantages in space capabilities.

Space has been militarized for decades.[1] During the Cold War, both the United States and the Soviet Union developed and deployed vast numbers of military communications, navigation, reconnaissance and intelligence satellites, as well as extensive support infrastructures, consisting of launch sites, and satellite monitoring and tracking facilities. Among the most important roles played by military satellites during the Cold War was to keep watch over the other side's nuclear forces, thereby helping to preserve strategic nuclear stability during that period. Increasingly, the US military has also used these same kinds of satellites to support ground, naval and air forces engaged in combat operations, most recently in Iraq and Afghanistan.

While space has been militarized for many years, it has not, at least as far as can be determined from unclassified sources, been weaponized. In other words, while satellites have been used to provide intelligence, targeting and other support to terrestrial-based forces and weapons, to

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[1] For an overview of issues related to the militarization and possible weaponization of space, see Barry D. Watts, *The Military Uses of Space: A Diagnostic Assessment* (Washington, DC: Center for Strategic and Budgetary Assessments, February 2001). For a see comprehensive introduction to technical issues related to space and space weapons, see David Wright, Laura Grego and Lisbeth Gronlund, *The Physics of Space Security*: *A Reference Manual* (Cambridge, MA: American Academy of Arts and Sciences, 2006).

date no country appears to have actually stationed weapons in space. Some analysts believe that the weaponization of space is inevitable and that the United States can and should move rapidly to acquire and field a range of space-based weapons. Others argue that the United States has more to lose than any other country if space is weaponized, and that taking steps in this direction would lead to the worst of both worlds—yielding little or nothing in terms of military advantage, and sparking or accelerating an arms race in space that the United States should, instead, be seeking to avert or at least delay as long as possible.

Space-based weapons could, in theory, be used to carry out at least four different missions. Specifically, they could be used to:

- defend against ballistic missile strikes;
- attack terrestrial-based (i.e., surface-based and airborne) targets;
- destroy or disable enemy satellites; and
- protect US satellites.

The wisdom and feasibility of acquiring and deploying one or more of these kinds of space-based weapons can only be determined through an analysis that takes into account a broad range of strategic, operational, technological, political, and financial considerations. Of all of these factors, historically, the area that has received the least attention has been the financial costs—specifically, the funding requirements—that would be associated with the acquisition and support of space-based weapons.

This is understandable to some extent. Weapon system cost estimates can only be as accurate as the quality of information available concerning the system's technical characteristics, overall system architecture and operational concept. In the case of space-based weapons, the quality of such information is typically poor. Moreover, estimating weapon system costs is notoriously difficult even in the case of relatively well-understood and mature technologies. In the case of space-based weapons, which in many instances would make use of technologies that are, at present, relatively immature and untested, the margin of error is likely to be far greater. On the other hand, an analysis of space weapons that does not consider the system's budgetary requirements is, at best, an incomplete one. At worst, such an analysis can provide a highly misleading picture of the system's potential cost-effectiveness.

The goal of this report is to raise the level of debate concerning the wisdom and value of acquiring and deploying one or more of the four types of space-based weapons noted above, by injecting into this debate a discussion of the potential budgetary costs associated with these systems, as well as possible terrestrial-based alternatives. For a variety of reasons such estimates are likely to be of only a rough, order-of-magnitude, quality—especially in the case of space-based weapons. Implicit in this report is the belief that, in a serious debate over policy choices, even rough cost estimates are better than no cost estimates at all. That said, readers are urged to treat these cost estimates carefully and to understand that, in some instances, they may be, quite literally, of only order-of-magnitude quality.

The cost estimates included in this report were derived from a variety of different sources. The three most important sources were various Congressional Budget Office (CBO) and Department of Defense (DoD) reports, and National Aeronautics and Space Administration (NASA) costing models. In some instances, the cost estimates were taken directly from CBO, DoD, NASA and other sources. In other cases, they were derived by the author based on the best available unclassified data. In many instances, this involved using CBO and other cost estimates for particular space-based weapons as a baseline from which to estimate the cost of other different (but similar) space-based weapons. Other important sources used in this report were studies by RAND and the American Physical Society. While these studies did not include cost estimates, they provided relatively detailed descriptions of certain space-based weapons technologies and system architectures, for which cost estimates—when supplemented with CBO and other cost data—could then be derived.

Of the four types of space-based weapons considered in this report, by far the greatest amount of detailed technical, operational and cost data is available for ballistic missile defense systems. Next best, in these respects, is the data available for proposed space-based prompt-strike systems. By comparison, while there is a significant amount of discussion surrounding space-based anti-satellite technologies, there is much less detailed information available concerning possible system architectures and, especially, potential costs. The available data on possible technologies, system architectures and costs is weakest of all in the case of space-based systems intended to protect other satellites. As a result, the cost estimates included in this report, although only rough in all cases, are likely to be especially speculative with respect to space-based anti-satellite (ASAT) weapons and defensive ("bodyguard") satellites.

The primary goal of this report is to provide cost estimates for various space-based weapon systems, as well as terrestrial-based alternatives, rather than to assess the effectiveness of such systems. However, the report does include some discussion of system effectiveness. This discussion is most extensive for ballistic missile defenses and prompt-strike weapons, where the CBO, RAND and APS studies noted above, to varying degrees, have provided estimates of effectiveness, at least in the absence of countermeasures. The discussion of potential system effectiveness is more speculative, and general, in the case of space-based ASATs and bodyguard satellites.

Based on the cost estimates identified or derived in this report and the estimates of system effectiveness also included in this analysis, this report offers a range of conclusions concerning the likely cost-effectiveness of various types of space-based weapons. In all cases, these findings should be taken as tentative and preliminary, given, among other things, the considerable amount of technological uncertainty that surrounds many of these systems. However, since a significant amount of cost and effectiveness data and analysis is available concerning potential space-based ballistic missile defense systems, in the case of these systems the conclusions offered in this report may be relatively robust. By contrast, since both the quantity and quality of such data and analysis is more limited in case of the other types of space-based weapons, especially for space-based ASATs and bodyguard satellites, the conclusions offered in this report concerning the overall cost-effectiveness of those systems should be treated as more tentative.

This report is organized into four chapters, each of which focuses on one of the four different types of space-based weapons noted above. In all cases, the focus is on the kinds of technologies and systems that it might be possible to deploy within the next 20 years. Chapter 1 covers space-based weapons intended for the boost-phase ballistic missile defense mission. Chapter 2 considers space-based weapons designed to attack terrestrial-based targets. Chapter 3 focuses on space-based ASAT weapons. Each of these chapters includes: a discussion of the basic technologies involved and possible system architectures; an estimate of the cost of acquiring and supporting such systems; some discussion of the potential effectiveness of these systems; and a limited discussion of the cost and effectiveness of possible terrestrial-based alternatives.

Chapter 4 of this report focuses on the use of space-based weapons designed to protect other satellites. For a variety of reasons discussed in that chapter, it is organized somewhat differently. This chapter includes only a relatively general discussion of bodyguard satellites and their potential cost and effectiveness. And, rather than discussing possible terrestrial-based alternative means of defending satellites from ASAT attacks, the consideration of alternatives included in this chapter focuses on a range of passive countermeasures that might be employed to accomplish this same mission. Among other things, the discussion and conclusions included in this chapter are more general and speculative than those provided in earlier chapters because of the especially limited availability of unclassified effectiveness and cost data concerning passive ASAT countermeasures.

Chapter 1: Space-Based Ballistic Missile Defenses

For the past several decades, a range of policymakers, analysts and others have advocated using space-based weapons to defend against the threat posed by ICBMs, SLBMs and shorter-range ballistic missiles. Of particular concern has been the challenge posed by long-range ballistic missiles armed with chemical, biological and, especially, nuclear warheads (so-called weapons of mass destruction, or WMD). During the 1980s, efforts to develop such defenses were focused primarily on countering the massive nuclear arsenal possessed by the Soviet Union. In the 1990s, attention shifted toward shorter-range ballistic missiles. Today, those advocating ballistic missile defenses generally, and space-based defenses in particular, most often point to the danger that North Korea, Iran or possibly some other "rogue" state will develop the capacity to strike the United States with WMD-armed ICBMs.

While neither North Korea nor Iran currently possess ICBMs, the former is developing the Taepo Dong 2 ICBM, which is expected to be capable of reaching at least Alaska and Hawaii.[2] In the case of Iran, US intelligence estimates that it could have an ICBM capable of reaching the United States by 2015.[3] The concern is greatest in the case of North Korea, since it already has nuclear weapons, which could be placed atop an ICBM. But Iran is also widely suspected to be pursing a nuclear weapons capability and, according to US officials, could possess nuclear weapons within the next 5–10 years.[4]

[2] National Air and Space Intelligence Center, "Ballistic and Cruise Missile Threat," NSAIC-1031-0985-06, March 2006, p. 17.

[3] Ibid.

[4] David Albright and Corey Hinderstein, "The Clock is Ticking, But How Fast?" The Institute for Science and International Security (ISIS), March 27, 2006, p. 1.

Although there is widespread concern about these developments, there is little consensus surrounding the question of what, if any, role ballistic missile defenses can or should play in helping to counter these potential threats. While some observers believe that such defenses could be highly effective, others argue that because of a range of technological, operational and other considerations, they are likely to prove neither effective, nor affordable. No aspect of this debate is surrounded by more controversy than the question of what role, if any, space-based defenses might play in countering this emerging threat.

This chapter has essentially three goals. First, to describe, in general terms, what a space-based ballistic missile defense system developed and deployed over the next two decades might look like. Second, to provide a rough estimate of what such systems would likely cost to acquire and support. Third, to explore, in a preliminary way, the cost-effectiveness of such systems by comparing their projected costs to estimates of both the cost (to the offense) of defeating these systems and the cost of acquiring alternative, terrestrial-based ballistic missile defense systems.

Overview of Space-Based Ballistic Missile Defenses

Two types of space-based weapons could, in theory, be used in the ballistic missile defense role: space-based kinetic-energy interceptors (SBIs), which would destroy or disable their target by hitting it with a high-speed projectile, or space-based laser (SBL) weapons, which would use a beam of electromagnetic radiation to kill their target.

Ballistic missile flight is divided into essentially three phases. During the boost-phase the rocket booster is ignited and the missile is lifted above the clouds and the densest layers of the atmosphere. For ICBMs, this phase lasts from roughly three minutes for solid fuel missiles, to four or five minutes for liquid fuel missiles. At the end of the boost-phase the rocket motor burns out and the booster is jettisoned. The missile's warhead then travels towards its target unpowered, on a ballistic trajectory (like an arrow launched from a bow). For ICBMs this midcourse phase lasts about 20 minutes. During the terminal phase, the warhead reenters the atmosphere to strike its target. This phase lasts about one minute. In the case of SLBMs and other shorter-range ballistic missiles, the duration of these various phases, as well as the overall flight, can be much shorter.

In theory, space-based weapons could be used to destroy ballistic missiles in either their boost or midcourse phases. For several reasons, most attention has focused on the possible use of these weapons for boost-phase defense. First, ballistic missiles are relatively easy to detect and track in this phase (because of their very bright booster plumes). Second, the boosters themselves are relatively large and soft targets. Third, destroying the missile at this stage obviates that need to distinguish between warheads and decoys, among the most serious challenges confronted by midcourse defenses.

Against these advantages, however, are a number of disadvantages. The most significant of these is the extremely short time available for engaging the target. Not only is booster burn time short, but much of the time available would have to be spent detecting and tracking the booster. According to a 2003 study, *Boost-Phase Intercept Systems for National Missile Defense*, conducted the American Physical Society (APS), “even state of the art sensors would require 45-60 seconds or longer to detect the launch of a potentially threatening rocket and determine its direction” (i.e., obtain a firing solution).[5]

Another problem inherent in boost-phase ballistic missile defense is that an intercept that successfully disabled a missile’s booster would probably not result in the destruction the missile’s warhead. An intercepted booster would rapidly lose thrust, but the ICBM’s warhead, which is only loosely coupled to the final stage of the missile, along with booster fragments and other debris, would likely continue to fall to earth on a ballistic trajectory. The warhead would fall to the earth short of its intended target, but possibly in populated areas. And, if launched from North Korea or Iran, those areas would not be in the attacking country, but could be in the United States or another country.[6] To ensure that an ICBM’s warhead had not attained the velocity needed to reach the United States, it would be necessary to intercept the booster as early as 40 seconds before it would normally burnout.[7]

The brief window available for boost-phase intercept means that, to be effective, any defensive system must have a very short response time. This response time is, in turn, driven by two factors: the proximity of the defensive system to the missile at the time of launch and the speed of the intercept mechanism.

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5 American Physical Society (APS) Study Group, *Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues*, July 2003, p. xxvii.

6 Ibid., p. xxvii.

7 Ibid., p. xxviii.

Advocates of space-based ballistic missile defense systems argue that such systems are ideally, and to some extent uniquely, suited for boost-phase defense because—unlike surface-based or airborne defense systems—they can be deployed within range of missile launch points anywhere in the world.

Among the most serious limitations of space-based boost-phase defense systems is the "abstentee" problem. Satellites in low earth orbit travel in their orbital plane at some 7–8 kilometers per second (km/sec). This means that a satellite in orbit at an altitude of 500 km, for example, will circle the earth once every 90 minutes. However, since the earth below is also spinning, the satellite will not travel above the same surface areas of the earth during each orbit. As a result of these dynamics, a space-based weapon will be within range of a particular location on the earth only a relatively small fraction the time.

Because of this absentee problem, the only way to keep a particular spot on the earth continuously covered is to maintain a constellation of space-based weapons in orbit. The precise amount of time a space-based ballistic missile defense system will spend within range of a particular spot—and thus the total number of such satellites that will be needed to maintain continuous coverage—will depend on both the specific characteristics of the defensive system's orbit (e.g., its altitude and inclination) and the speed of its interceptor missile, or range of its laser.

Space-Based Kinetic Energy Interceptors

If the United States was to deploy a space-based boost-phase ballistic missile defense over the next 15–20 years it would most likely consist of an SBI constellation. Although developing and deploying such a system would require some significant technological advances, this technology is generally substantially more mature than that needed to support the deployment of a space-based laser defense. In 2004, CBO released a study that assessed the feasibility and cost of various boost-phase defenses designed to protect the United States from an extremely limited North Korean or Iranian ICBM threat.[8] The options assessed by CBO included two SBI options.

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8 David Arthur and Robie Samanta Roy, *Alternatives for Boost-Phase Missile Defense* (Washington, DC: CBO, July 2004).

Under one of these options, CBO concluded that assuming the United States could develop and deploy an SBI capable of speeds of 4 km/sec, and North Korea and Iran were able to develop only relatively slow burning liquid fuel ICBMs, it would need a constellation consisting of 368 SBI to provide continuous coverage of potential ICBM launch sites in the two countries.[9] This estimate was based on the assumption that the United States would always want to have at least two SBIs within range of those sites, to increase the likelihood that a successful intercept could be made (consistent with current Missile Defense Agency doctrine). These figures imply an "absentee ratio" of about 184-to-1. In other words, on average, each individual SBI would be on station within range of North Korean or Iranian launch sites only about 0.5 percent of the time. The other 99.5 percent of the time they would be out of position, either over the ocean of over other countries.

In the second option, CBO assumed that interceptor speed could be increased to 6 km/sec. In this case, the effective range of each SBI would grow and, as a result, the absentee ratio would decline. Specifically, the size of the required constellation would drop to 156 SBIs.[10] According to CBO, however, developing this capability would require a "technological leap" in kill vehicle miniaturization.[11]

Even if the technology worked perfectly, these SBI constellations would have very modest capabilities. Either constellation would be capable of intercepting a single ICBM launched alone. However, assuming that two SBIs would be directed—as soon as a firing solution could be generated—against the first booster detected, and that the attacker would time the launch of its ICBMs to maximize their odds of penetrating the defense,[12] neither constellation would have any capability against additional ICBMs launched from the same area within 10 minutes of the first (after roughly 10 minutes the orbital motion of the satellites would bring two more SBIs within range of the area).[13] In turn, assuming the

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9 Ibid., p. 43.

10 Ibid.

11 Ibid., p. 25.

12 The effective intercept ranges of the SBIs making up the constellation would overlap to some extent. Thus, at any given time, at least two, and as many as six, SBIs might be within range of a particular ICBM launch site. However, because the SBIs in the constellation would be traveling in predictable, observable orbits, the attacker could easily time the launch of its ICBM(s) to occur during one of the (frequent and regular) intervals in which only two SBIs would be within range.

13 Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. 36.

attacker is neither "blissfully oblivious" nor "willfully self-destructive,"[14] it is probably prudent to assume that he would take advantage of this fundamental limitation of space-based boost-phase defenses and launch his ICBM force in an appropriately-timed salvo.

Moreover, both of these SBI constellations would be even less capable of defeating an attack by short- or medium-range ballistic missiles. This is because the booster burn time for such missiles is typically only one-half to two-thirds as long as it is for an ICBM. As a result, in the case of either of these constellations, an SBI generally would not be close enough to intercept successfully the launch of even a single short- or medium-range missile.

CBO estimates that, depending on DoD's success at controlling weapon system cost growth, acquiring and operating (over 20 years) the first of these constellations (with 368 SBI) would cost some $60–84 billion (2007 dollars[15]), while the second—more technologically demanding and risky—of these constellations (with 156 SBI) would cost $29–43 billion.[16] These estimates include the cost of developing these systems, launching them into orbit[17] and replenishing the satellites in the constellations.[18] For this expenditure, the United States would gain possession of a missile defense system that could confidently be expected to intercept only a

14 Bob Preston, Dana J. Johnson, Sean J.A. Edwards, Michael Miller, and Calvin Shipbaugh, *Space Weapons, Earth Wars* (Santa Monica, CA: RAND, 2002), p. 118.

15 Unless otherwise noted, all cost and funding figure cited in this report are expressed in 2007 dollars.

16 Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. 42.

17 Unless otherwise noted, the acquisition cost estimates for space-based systems provided in this report include costs associated with launching the weapons into space. Launch costs today average about $11,000 per kilogram of payload placed in low-earth orbit. (Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. 46.) Advocates of space weapons often point to future improvements in space launch capabilities as a key means of reducing the cost of space weapons. However, it appears unlikely that there will be a technological breakthrough over the next 20 years that will lead to major improvements in the efficiency and cost of space launch services. (See, Michael E. O'Hanlon, *Neither Star Wars Nor Sanctuary* (Washington, DC: Brookings Institution Press, 2004, pp. 82–85; and Paul B. Rehmus, *Alternatives for US Space-Launch Capabilities* (Washington, DC: CBO, October 2006.)

18 CBO assumes that each SBI would have operational service life of about 7 years. Arthur and Roy, *Alternatives for Boost-Phase Missile Defense,* p. 49. Thus, CBO estimates that supporting constellations of 368 and 156 SBI, respectively, would require the purchase of 848 and 384 replenishment SBIs over the system's presumed 20 year operational life. Ibid., p. 28.

single ICBM launched against it, even if the technology worked perfectly. The interception of any additional ICBMs would essentially be dependent on the attacker (inexplicably) launching its missiles in a manner (e.g., individually, at 10 minute intervals) designed to accommodate the extremely limited capabilities of the US SBI constellation.

Moreover, the CBO study may be too optimistic in terms of both technical requirements and capabilities, and the costs associated with fielding an SBI constellation over the next two decades. In its 2003 study of boost-phase ballistic missile defenses, the APS concluded that defending the United States against a single liquid-fuel ICBM launched from North Korea or Iraq would require fielding a constellation consisting of some 700 SBIs, roughly double the number of interceptors projected in the larger of the two CBO options. Among the main reasons for this difference is the APS study's assumption that the adversary's liquid-fuel ICBMs would have a four minute, rather than five minute, booster burn-time—significantly reducing the time available for intercept, and thus the range, of each SBI.[19] In terms of its technical specifications, the SBI in the APS study closely resembles the larger and slower of the two SBIs considered by CBO—with this less capable system representing what the APS believes is technologically achievable within the next 15 years.[20] Extrapolating from CBO cost data, a reasonable estimate is that this larger SBI constellation would have 20 year lifecycle costs of some $102–138 billion.[21]

In order to increase the number of ICBMs that the SBI constellations discussed above could theoretically be capable of intercepting from a single missile to two missiles (without the assistance of a blissfully oblivious or self-destructive adversary), the number of SBIs in orbit would have to be doubled—with a commensurate increase in system costs of tens of billions of dollars. Worse yet, the additional increment of protection this would buy the United States could, in turn, be completely offset and undercut by the adversary's purchase of a single additional ICBM. And for a country that has already developed and produced an ICBM, additional missiles would likely cost no more than several tens of millions of dollars each to

19 Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. xii.

20 APS, *Boost-Phase Intercept Systems for National Missile Defense*, p. xxvi.

21 Author's estimate. It assumes that due to economies of scale and learning curve efficiencies, doubling the number of SBI to be procured and supported would cause less than a doubling of costs. The assumptions about these factors used in this estimate appear to be roughly consistent with those used by CBO in its estimates of the impact on costs of acquiring additional SBI. See, Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. 35.

produce, and perhaps less. As a result, notwithstanding the enormous wealth of the United States relative to countries such as North Korea and Iran, this may not be a case where the United States could prevail by simply outspending its opponent.

Countermeasures

Nor would launching missiles in salvos or, if necessary, buying additional ICBMs, constitute the only effective means of defeating an SBI constellation. Other options include the use of solid fuel ICBMs or decoy boosters, and attacking SBIs with ASAT weapons. The use of these additional countermeasures would render an SBI constellation even less cost-effective than the analysis above suggests.

The assumption, incorporated into the various options described above, that North Korea and Iran would be unable to acquire solid fuel ICBMs, may be overly optimistic. The availability of solid-propellant rocket technology is growing,[22] and such a booster could be developed using even 40-year old technology. As a result, according to US intelligence estimates, North Korea and Iran could develop or acquire solid fuel ICBMs within 10 to 15 years.[23] If those countries could acquire such ICBMs, which have substantially shorter booster burn times than liquid fuel missiles, the size of the SBI constellations discussed above would have to be dramatically increased to maintain the same—at best, minimal—level of effectiveness.

CBO estimates that if North Korea and Iran possessed solid fuel rather than liquid fuel ICBMs, the number of SBIs in the two constellations would have to be more than tripled. Specifically, in the case of the 4 km/sec interceptor, the number of SBIs in the constellation would have to be increased to 1,308. In the case of the 6 km/sec interceptor, the size of the constellation would have to be increased to 512.[24] The cost of these two options would grow to $175–241 billion and $64–86 billion, respectively. Similarly, the 2003 APS study concluded that to defend the United States against an attack by a single solid fuel ICBM, the size of the constellation would have to be increased to some 1,600 SBIs.[25] A reasonable estimate for the cost of an SBI constellation of this size would

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22 APS, *Boost-Phase Intercept Systems for National Missile Defense,* p. S150.
23 Ibid., p. xxxv.
24 Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, p. 35.
25 APS, *Boost-Phase Intercept Systems for National Missile Defense,* p. xxxviii.

be some $210–290 billion. And, again, these enormous expenditures would be for constellations that could be overwhelmed by the salvo launch of as few as two (in this case, solid fuel) ICBMs.

Another possible countermeasure would be to use decoy boosters. Such boosters would mimic the plume characteristics of an ICBM, but would be much less costly to procure, among other things, because they would carry no nuclear (or other WMD) warheads, and would not need the same control and guidance capabilities.[26] Moreover, it would likely be sufficient for a decoy booster to fool an SBI's targeting sensor during only the first minute or two (or possibly less) of the boost-phase, given the amount of time needed for an SBI to effectively detect, track and then intercept its target, and the need to commit to a particular target as quickly as possible.

Still another potentially cost-effective countermeasure to an SBI defense would be to attack the SBIs themselves. In this case, the attacker would use ASAT capabilities to destroy the small number of SBIs (generally, two, in the various constellations discussed above) that would, at any given time, be in orbit within range of any particular ICBM launch site. The attacker would then, immediately thereafter, launch its ICBM(s) through the "hole" in the SBI constellation created by this ASAT attack.

In considering the cost-effectiveness of space-based ballistic missile defense systems, and ballistic missile defenses generally, it is also important to recall that ballistic missiles are only one of many means that North Korea, Iran or another potential adversary might use to attack the United States with nuclear warheads or other WMD. In fact, such an attack may be among the least likely ways any adversary would choose to attack the United States. Alternative means of delivering WMD include the use of aircraft or cruise missiles, ships entering US harbors, or smuggling the weapons into the country. Space-based ballistic missile defense systems would provide no protection against these threats. Furthermore, any of these alternative means could be acquired with far less difficulty and at far lower cost than an ICBM capability. On the other hand, ICBMs may offer some advantages over various alternative means of delivering WMD (e.g., in terms of the ability to maintain centralized control, and strike targets rapidly).

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[26] Ashton B. Carter, *Directed Energy Missile Defense in Space* (Washington, DC: Office of Technology Assessment, April 1984), p. 50.

Space-Based Laser Defenses

Developing and deploying an SBL constellation within the next two decades would be a much more technologically ambitious undertaking. Indeed, it is far from clear that such a system—even one of only very modest effectiveness—could be deployed within this timeframe. The Department of Defense (DoD) itself projects that an SBL constellation probably could not be made operational until sometime after 2020,[27] or even 2035.[28] Similarly, in a 2002 study, CBO assumed that such a system could become fully operational only in 2025 or beyond.[29]

A 2002 RAND study described a variety of possible SBL weapon systems and constellations that might be developed and deployed by the United States.[30] The base case constellation consisted of 24 SBLs orbiting at an altitude of about 1,250 km. The SBL in this constellation consisted of a hydrogen-fluoride (HF) laser operating with a nominal power level of 5 megawatts, and a 10 meter-diameter primary mirror.[31] These specifications closely resemble those projected by the Missile Defense Agency (MDA), in recent years, for an SBL system that might be deployed after 2020.[32] According to the RAND study, this SBL constellation would be capable of engaging and killing a single medium-range (3,375 km) ballistic missile, assuming (as in the SBI examples) that the attacking country's missiles were launched from a single area simultaneously or in relatively rapid succession, and timed to maximize their ability to penetrate the defense.[33]

This system would be more effective against an ICBM threat because of the longer booster burn times of these missiles (compared to medium-range ballistic missiles). In this case, the constellation could destroy

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[27] Defense Science Board (DSB) Task Force, *High Energy Laser Weapon Systems Applications* (Washington, DC: Departmetn of Defense, June 2001), p. 13.

[28] Dr. Tom Hussey, ST Tech Advisor, High Power Microwaves, Directed Energy Directorate, Air Force Research Laboratory, "Directed Energy Possibilities—2035," briefing, March 2005. This briefing does not include ballistic missile defense as one of the concepts that are "likely to occur [by 2035] in some form based on today's trends." Instead, it appears to include this mission within a less likely class of concepts that represent "potential breakthrough capabilities." Slide 6.

[29] CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," January 2002, p. 2.

[30] Preston et al, *Space Weapons, Earth Wars*.

[31] Ibid., p. 121.

[32] DSB, *High Energy Laser Weapon Systems Applications,* p. 18–21.

[33] Preston et al, *Space Weapons, Earth Wars*, Figure A-7, p. 117.

perhaps half a dozen boosters,[34] assuming that the adversary would seek to maximize the attack's penetrating capability by salvo launching its ICBMs at the most opportune time. If the United States could develop and deploy a more advanced SBL system, this theoretical capability could be improved. For example, holding all other design specifications constant, an SBL equipped with a chemical oxygen iodine laser (COIL), rather than an HF laser, should be able to intercept four times as many ICBM boosters.[35] However, since this technology is less mature than HF technology,[36] it seems even less likely that such a system could be developed and deployed within the next two, or even three, decades.[37]

In each of these cases, it is assumed that the threat missiles would be solid fuel missiles. As noted earlier, the assumption that North Korea or Iran could not develop a solid fuel booster over the next 20 years, but would instead have to rely on older liquid fuel technology, may be unrealistic. Whatever the merits of that assumption in the case of an SBI constellation, however, it seems especially unrealistic when considering the likely effectiveness of a future SBL constellation. Since, even if a decision were made to move ahead with the acquisition of such a system over the next few years, it would probably not even *begin* its operational life until, at the earliest, the 2020–25 timeframe. As such, the assumption that a future SBL constellation would face solid fuel ballistic missiles seems appropriate.

RAND did not attempt to estimate the cost of the various SBL constellations described in its 2002 report. The report did, however, note that SBLs "capable of destructive effects will be large and expensive."[38]

34 Authors estimate based on RAND data.

35 This is because the wavelength of the COIL is about one-half that of the HF laser, and laser intensity is inversely proportional to the square of the lasers' wavelength. In other words, all else being equal, the shorter the wavelength the more focused, and thus intense, the laser's beam.

36 Preston et al, *Space Weapons, Earth Wars*, p. 126.

37 The 2002 RAND study also concludes that a SBL constellation's performance could be improved somewhat by deploying a larger number of less powerful SBLs. For example, it estimates that a constellation consisting of 120 one-megawatt HF SBLs, which might cost no more to operate and support than RAND's base case SBL constellation (of 24 five-megawatt HF SBLs), would be capable of intercepting up to 12 ICBMs, even if they were launched in an appropriately-timed salvo. (Preston et al, *Space Weapons, Earth Wars*, p. 125.) Since few other sources (including DoD) appear to have focused much attention on this approach, it is not discussed further in this report.

38 Preston et al, *Space Weapons, Earth Wars*, p. 26.

> [A] single space-based laser for missile defense would be something like the combination of a next-generation space telescope with a large rocket engine and its propellant tanks. The combination is challenging because the telescope is a precision instrument requiring precise, stable pointing despite being subjected to the noise and vibration of a large rocket engine firing. Some technologies would have the additional challenges of highly corrosive fuel and exhaust from the laser.[39]

An Office of Technology Assessment (OTA) study noted the difficulties associated with effectively targeting a ballistic missile with a laser.

> Aiming [laser] radiation at a moving target thousands of kilometers away requires highly accurate tracking and pointing. Typically, a beam spot of roughly a meter in diameter is envisioned for attacking today's missiles in their boost-phase. To hit a target with an error of tenths of a meter at a distance of thousands of kilometers requires accuracy of about a tenth of a microradian. This is equivalent to hitting a television set in Los Angeles with a beam fired from directly over New York City.[40]

Although the RAND study did not include cost estimates, both DoD and CBO have provided cost estimates for SBL constellations that appear to resemble relatively closely the base case system described by RAND. In 1999, a DoD report, the *Space High Energy Laser Architecture and Affordability Study*, estimated that an SBL constellation consisting of 24 HF-laser battle stations with technical specifications similar to those projected in the RAND study would cost $92 billion to acquire and operate over its lifetime.[41]

In 2002, CBO estimated that acquiring and supporting such a constellation would cost far more than projected by DoD. Specifically, CBO estimated that the 24-SBL constellation then being pursued by the MDA would cost $61–76 billion to acquire, and would have annual

39 Ibid.

40 Office of Technology Assessment (OTA), *Ballistic Missile Defense Technologies* (Princeton, NJ: Princeton University Press, 1986), p. 148.

41 DSB, *High Energy Laser Weapon Systems Applications*, p. 59.

satellite replacement and operating costs of $5–6 billion.[42] Assuming a 20-year life for this constellation, CBO's estimate implies a total cost of about $157–196 billion (see Figure 1). This would make the projected SBL constellation substantially more expensive to acquire and operate than most of the SBI options described earlier in this section.

A potentially less costly approach to a boost-phase laser defense would be to field a constellation of space-based relay mirrors in combination with either space-based or ground-based lasers. In such a system, most, or all, of the SBLs in orbit would be replaced by relay mirrors. These relay mirrors would refocus and redirect the laser energy emitted by a relatively small number of SBLs or ground-based lasers to provide the same coverage possible with a constellation comprised entirely of SBLs.

One of the main advantages of this approach would be that the number of SBLs that would need to be deployed could be substantially reduced, or—if ground-based lasers were used—eliminated entirely. This, in turn, could result in cost savings. While possibly significant, however, the savings would probably not be dramatic.

According to one estimate, relay mirrors used in such a system would weigh about 20 percent less than the SBLs they would replace,[43] and cost 25 percent less.[44] Assuming this estimate is correct, a hypothetical boost-phase ballistic missile defense system consisting of 24 relay-mirror satellites and three SBLs,[45] for example, would be projected to cost about 15 percent less to procure than a constellation consisting of 24 SBLs. However, *total* savings for such a system would be less than 15 percent. Most importantly, this is because all of the R&D costs associated with acquiring a space-based laser system would still be incurred, along with some additional R&D costs peculiar to development of the relay mirrors. These considerations suggest that the 20-year lifecycle costs

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42 CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 23. CBO assumes that each satellite would have a service life of eight years. Thus, three replacement SBLs would have to be deployed each year to keep the constellation size at 24.

43 Maj. Steven G. Leonard, "Laser Options for National Missile Defense," Air Command Staff College, Air University, April 1998, p. 21.

44 Col. Loverro, "Space-Based Lasers: The Path Ahead," briefing for USAF SMC/AD, December 17, 1997, slide 15 (cited in Leonard, "Laser Options for National Missile Defense," p. 21).

45 This constellation is described in Leonard, "Laser Options for National Missile Defense," pp. 66–75.

of a boost-phase missile defense constellation consisting of three SBLs and 24 relay mirrors would be about 10 percent less than for the 24-SBL constellation described earlier, or some $142–176 billion.[46]

That the savings associated with using a combination of SBLs and relay mirrors—rather than SBLs alone—would probably not be dramatic is also suggested by the findings of DoD's 1999 *Space High Energy Laser Architecture and Affordability Study*. The report concluded that while there was a "high probability" that a constellation of 24 SBLs could be fielded in the 2020 timeframe, it *might* be possible to field—at lower cost, though with higher technological risk—a comparably effective constellation consisting of six SBLs and 12 relay mirrors. DoD estimated that such a system would cost about $78 billion to acquire and support over its lifetime. This is about 17 percent below its estimate of the cost of a 24-SBL constellation. Using CBO's estimate for the cost of a 24-SBL constellation as a baseline (rather than DoD's much lower, and probably less realistic, estimate), implies total (20-year lifecycle) costs for this alternative of about $131–162 billion.

For a number of reasons, a boost-phase laser defense that included relay mirrors would, in some ways, be more technologically challenging than a system comprised entirely of SBLs. One problem that would affect such a system is that the laser energy used to destroy attacking ballistic missile boosters would have to be directed over far greater distances (from the laser to one or more relay mirrors before reaching the intended target). This is a potentially serious problem, since a beam of laser energy (like all electromagnetic radiation) becomes less intense as it travels out from its source—with the intensity falling off as the square of the distance (meaning that as the distance traveled doubles, the intensity of the beam drops by a factor of four). Other problems associated with the design and operation of relay satellites include the following:

> Relay mirrors present unique challenges in beam control and dual line-of-sight because of the need to collect laser light from ground-, airborne-, or space-based platforms and relay it through a different optical system, at a different location. Meeting this set of needs requires specific beam control solutions. Furthermore, the two independent optical systems have to point and track towards different

[46] This estimate assumes that, as in the case of the SBL system described in the CBO report, R&D costs would account for roughly 30 percent of this system's total acquisition costs.

> locations. This implies a hierarchy of structural and optical control never before demonstrated .... Relay mirror satellite concepts also pose unique problems for satellite attitude control and momentum management.[47]

Rather than placing a combination of SBLs and relay mirrors in space, another option would be to support a constellation of space-based relay mirrors with a small number of ground based lasers. A potentially significant advantage of basing the laser itself on the ground is that it would reduce the difficulty and cost of refueling the laser, as well as ease maintenance requirements. A major problem with this option, however, is that some of the most technologically mature lasers, such as the HF laser, are incapable of penetrating the atmosphere.

In theory, the free electron laser (FEL), might be the laser best suited for use in this role. According to DoD, at the optimum FEL wavelength, the atmospheric distortion could be effectively compensated for at power levels appropriate for the ballistic missile defense mission.[48] However, in important respects, FEL technology, which produces laser radiation by sending very fast electrons through a magnetic field, is still relatively immature. Among other things, the power output of FEL lasers is presently far too weak—by a factor of about one thousand—for them to be used effectively in the missile defense role.[49] As a result, it seems highly unlikely that a boost-phase ballistic missile defense composed of ground-based FEL lasers will be fielded over the next twenty years.

A further problem with the ground-based laser concept is that any laser, even the FEL, can be rendered ineffective by cloud cover. This means that, at a minimum, several ground based lasers would have to be constructed at different locations around the United States to ensure that at least one would always be free of cloud cover.

Even assuming that the United States could develop and deploy a space-based boost-phase defense system supported by ground-based lasers, it is unclear whether this would result in significant cost savings compared to an entirely space-based laser defense. In its 2002 report, RAND considered one ground-based laser option. The hypothetical system consisted of two ground-based FEL and 24 space-based relay mirrors.

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47 DSB, *High Energy Laser Weapon Systems Applications*, p. 60.
48 Ibid., p. 53.
49 O'Hanlon, *Neither Star Wars Nor Sanctuary: Constraining the Military Uses of Space*, p. 72.

RAND did not provide an estimate of the cost of this system. However, extrapolating from the CBO and other estimates discussed earlier, it is not clear that such a system would cost substantially less to acquire and deploy than a system comprised either entirely of SBLs, or a combination of SBLs and relay mirrors.

Assuming, once again, that each relay mirror would cost about 25 percent less than an SBL to produce, the space-based component of this system would be projected to cost some $34–39 billion to procure. Estimates provided by DoD suggest that that constructing, at a single site, a relatively small, low-power ground-based laser intended for an ASAT role would cost $2–3 billion.[50] By comparison, it has been estimated that constructing a much larger ground-based laser, of the type that would be needed to support the boost-phase intercept mission, might cost anywhere from roughly $5 billion to as much as $30 billion.[51] If each ground-based laser could be constructed for about $15 billion, these figures suggest that a constellation of 24 relay mirrors supported by two ground-based lasers would cost some $49–54 billion to procure. Assuming the development costs associated with this system would be comparable to those projected for the SBL constellation described in CBO's 2002 report, initial acquisition costs for this system would reach some $55–77 billion. Assuming $4–5 billion a year in satellite replacement and operating costs, this implies total 20-year lifecycle costs for such a system of some $128–167 billion.

While, as in the case of the SBI constellations discussed earlier, a full-blown cost-benefit analysis of a boost-phase space-based laser system is beyond the scope of this report, the basic calculus appears unpromising. In theory, at least in the absence of countermeasures, a space-based laser system could be constructed that would be substantially more effective in the missile defense role than an SBI constellation. As noted above, data provided by RAND suggests that a constellation of 24 SBLs, equipped with HF lasers, and very similar to the systems projected in various DoD studies, might be capable of destroying as many as a half dozen solid-fuel ICBMs, even if launched in a single, well-timed salvo. This is significantly better than either of the SBI systems described earlier, which—in the event of an attack designed to maximize the odds of penetration—would, at best, be capable of intercepting a single *liquid fuel* ICBM. However, the technology needed to develop and deploy an SBL constellation is considerably less mature than it is for an SBI system.

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[50] DSB, *High Energy Laser Weapon Systems Applications*, p. 49.

[51] Lt. Col. William H. Possel, "Laser and Missile Defense: New Concepts for Space-Based Laser Weapons," Occasional Paper No. 5, Center for Strategy and Technology, Air War College, Air University, July 1998, p. 18.

Equally important, although in theory this SBL system could—again, at least in the absence of countermeasures—be significantly more effective than an SBI system, it might also cost far more to acquire and support. And, as in the case of an SBI defense, it would still be possible for a potential adversary to construct additional ICBMs—in order to ensure penetration of the defense—for far less than it would cost the United States to expand the size of the SBL constellation to prevent such penetration. It seems unlikely that it would prove cost-effective for the United States to spend on the order of $100 billion, or more, for a system that could be overwhelmed by a potential adversary's acquisition of perhaps a half dozen ICBMs—which, for a country that had already developed an ICBM capability, would likely cost no more than several hundred million dollars, and possibly less.

The cost-exchange ratio would be more favorable for the defense if the United States could develop and deploy a more advanced SBL system—such as one that used chemical oxygen iodine lasers. As noted earlier, in the absence of countermeasures, shifting to such a system might increase the number of ICBMs that could be intercepted by a factor of four, compared to a constellation comprised of HF lasers. However, since this technology is less mature, it is even less likely that such a system could be fielded over the next 20 years. Moreover, even assuming such a system could be successfully fielded, the cost-exchange ratio would remain heavily weighted in favor of the offense.

Worst yet for the defense, for planning purposes, it must be assumed that the offense would also employ various countermeasures to help defeat an SBL constellation. The employment of such countermeasures could greatly reduce the already relatively modest ballistic missile defense capabilities of an SBL constellation.

Countermeasures

The countermeasures to an SBI constellation, discussed earlier in this chapter, could also be used to help defeat an SBL constellation designed for boost-phase defense. Beyond these general countermeasures, there are also several to which SBL systems, in particular, would be vulnerable.

In the case of the SBL options described above, it was already assumed that the threat missiles would be solid, rather than liquid, fuel missiles. However, it is possible that North Korea, Iran or a similar country could deploy even faster burning boosters. According to the APS study, *Boost-Phase Intercept Systems for National Missile Defense*, it would be "practically impossible for any interceptor rocket to reach an ICBM with a boost-phase of two minutes or less.[52] Such a fast-burning booster would also severely reduce, though not necessarily entirely eliminate, the effectiveness of an SBL constellation.

ICBMs with booster burn times of as little as one minute could be constructed by the United States,[53] and could be "easily accomplished at little sacrifice in useable ICBM payload."[54] It is less certain whether and, if so, when, countries like North Korea and Iran could deploy boosters with burn times of two minutes or less. But given the relatively distant time horizon during which an SBL system might be deployed, and remain operational (e.g., through 2040 and beyond) it is difficult to discount the possibility that an adversary could deploy such a booster.

As in the case of an SBI constellation, decoy boosters and ASAT attacks could also prove to be effective countermeasures. The threat of ASAT attack may be even greater in the case of an SBL constellation. As will be discussed in more detail in Chapters 3 and 4 of this report, the interplay between ASAT capabilities and techniques to defend and protect satellites is complex, and it is difficult to generalize as to where the advantage lies. However, as one author has noted, "in the specific case of large battle stations in low-earth orbit [like SBLs designed for ballistic missile defense] it would seem that the advantage is very likely to be with ASAT" capabilities, not protective satellite measures.[55]

> For one thing, the offense need not destroy a large number of defensive [i.e., ballistic missile defense] satellites, but only "cut a hole" in the defensive constellation. Second, the traditional military refuges all offer complications: concealment from radar, optical, infrared, and electronic detection, while possibly successful for small payloads in supersynchronous orbits [i.e., orbits beyond geosynchronous], is impractical for large, complex spacecraft at most a few thousand [kilometers] from the earth's surface; decoy satellites must generate heat, stationkeep, and give status reports ... hardening imposes

52 APS, *Boost-Phase Intercept Systems for National Missile Defense*, p. xxix.

53 Carter, *Directed Energy Missile Defense in Space*, p. 8.

54 Ibid., p. 48.

55 Ibid., p. 46.

> weight penalties, and massive shields could interfere with the constant surveillance and instant response required of the defense; [and] proliferation is useless for expensive satellites facing inexpensive ASAT methods."[56]

Like all satellites, those in an SBL constellation also suffer from the fact they would follow completely predictable orbits, making them "in effect fixed targets."[57]

SBL constellations would be susceptible to several other countermeasures as well. One simple option would be to design the booster to rotate during its flight. Doing so would force the laser to illuminate a larger spot, thereby increasing the time need to effect a kill by perhaps a factor of three.[58]

Another option would be to cover the booster with an ablative coating that would dissipate the laser energy. According to one estimate, adding a gram of heat-shield material (similar to that used on reentry vehicles) to each square centimeter of booster skin would triple the dwell time needed to effect a kill, with the extra weight of the coating having only a relatively modest impact on the missile's payload.[59] A better option might be to coat the booster with a much lighter ablative coating such as cork. An SBL having the same specifications as those included in the RAND study's base case, firing at a booster rising above the atmosphere 3,000 km away (which would be a typical range for a 24-SBL constellation), would require about one minute to burn through a 3 centimeter-thick coating of cork[60]—imposing on the SBL at least a several-fold increase in necessary laser dwell time.

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[56] Ibid.

[57] Ibid.

[58] Ibid., p. 49.

[59] Ibid.

[60] An SBL with a deuterium fluoride (3.8-micron wavelength), 3-megawatt laser and 3-meter mirror, operating at a range of 3,000 km would reportedly take 20 minutes to burn though 3 centimeters of cork. Bruce M. DeBlois, Richard L. Garwin, R. Scott Kemp, and Jeremy C. Marwell, "Space Weapons: Crossing the US Rubicon," *International Security,* Vol. 29, No. 2 (Fall 2004), p. 73. This implies that an SBL with a hydrogen fluoride (2.7-micron wavelength), 5-megawatt laser and 10-meter mirror (the specifications of the SBL included in the 2002 RAND study's base case), operating at the same range, would take about one minute to burn through such a coating.

These estimates suggest that simply rotating the ICBM booster could be sufficient to reduce the number of ICBMs a 24-SBL constellation, like RAND's base case system, could be expected to intercept successfully—even if the technology worked perfectly—from roughly half-a-dozen missiles to perhaps two ICBMs. If combined with other relatively simple countermeasures, such as the use of ablative coatings or decoy boosters, it could well prove impossible for such a defensive constellation to intercept even a single ICBM. This conclusion is also consistent with CBO's finding that defending against "one or more" *hardened* missiles could require "significantly larger constellations" than the 24-SBL system CBO considered in its 2002 study.[61]

Figure 1: Cost Estimates for Illustrative Limited-Capability Ballistic Missile Defense Systems
(in 2007 dollars)

System	Cost*
Space-Based	
Space-Based Interceptor	
4 km/sec interceptor (CBO)	$60–84 billion/$175–241 billion**
6 km/sec interceptor (CBO)	$29–43 billion/$64–86 billion**
4 km/sec interceptor (APS)	$102–138 billion/$210–290 billion**
Space-Based Laser	
SBL	$157–196 billion
SBL/Relay Mirrors	$131–176 billion
GBL/Relay Mirrors	$128–167 billion
Terrestrial-Based	
Surface-Based Boost-Phase Interceptor	$17–40 billion
Airborne Interceptor	$16–23 billion^
Airborne Laser	$15 billion^
Ground-Based Midcourse Interceptor	$32–34 billion
Sea-Based Midcourse Interceptor	$64–80 billion

* Estimates generally include cost to acquire the system and (once fully deployed) operate it for 20 years.
** System designed to counter liquid/solid fuel missiles.
^ Includes only acquisition costs.
Sources: See text for description of sources and methodology.

61 CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 29.

Alternative Terrestrial-Based Ballistic Missile Defense Systems

The simple cost-exchange analysis discussed above suggests that the cost of developing and deploying a space-based ballistic missile defense system would—at least based on the technologies likely to be available over the next 20 years—probably far exceed the cost to the offense of penetrating or overwhelming such a defense. Indeed, the cost-exchange ratio appears to be so one-sided that despite the United States' vast edge in wealth, compared to countries like North Korea and Iran, this may be a case where the United States cannot succeed by simply outspend its adversary.

This appears to be true even if the attacker were to take no special precautions other than to time its strike prudently and launch its ICBMs in salvos. The employment of other countermeasures, especially if used in combination, would render a space-based ballistic missile defense even less cost-effective—quite possibly by an order-of-magnitude or more.

Given the one-sided nature of the offense-defense calculus described above, it seems highly doubtful that space-based ballistic missile defenses would prove a sound and cost-effective investment for the United States over the next 20 years, even assuming there was no more cost-effective alternative means available for defending against ballistic missile attack. It is worth noting, however, that a number of alternative terrestrial-based ballistic missile defense systems either exist, or are under development. In other words, SBI and SBL constellations are by no means the only types of systems available to intercept ballistic missiles.

In general, these terrestrial-based alternatives would be less costly, and typically far less costly, to develop, deploy and support than the space-based options considered in this chapter. The various types of terrestrial-based weapon systems that could be used for ballistic missile defense include the following:

- Surface-based boost-phase kinetic-energy interceptors;
- Airborne kinetic-energy interceptors;
- Airborne lasers; and
- Surface-based midcourse kinetic-energy interceptors.

In the remainder of this chapter, each of these alternative options is discussed in turn. While it includes some discussion of capabilities and effectiveness, the focus of this discussion is on the budgetary cost of each option.

Surface-Based Boost-Phase Kinetic-Energy Interceptors

In its 2004 study of boost-phase ballistic missile defenses, CBO analyzed three surface-based defense systems. Such a system would consist of a small number of high-speed ground- or sea-based interceptor missiles located at a handful of sites near Iran and North Korea. The life cycle costs of these systems range from $17–26 billion for a 6 km/sec system to $27–40 billion for a 10 km/sec system.[62] These cost estimates are generally lower than those for the SBI constellations described earlier, and dramatically lower than those for any of the SBL constellations discussed in this chapter. These alternative systems are also generally less technologically demanding, allowing them to be deployed more quickly than an SBI constellation, and probably far earlier than an SBL constellation.[63]

Nor does the CBO study suggest that surface-based boost-phase defenses would, in general, be any less effective than a space-based system. Like the SBI options discussed in this report, all of the surface-based boost-phase defense options considered by CBO would—assuming the technology could be made to work effectively, and in the absence of countermeasures—have a limited capability to counter a North Korean or Iranian arsenal consisting of a handful of ICBMs. However, the various systems would not have identical capabilities. As CBO notes:

> Each [boost-phase ballistic missile defense] design has inherent advantages and disadvantages in such matters as cost, potential areas of coverage, capability against

[62] The third option consisted of an 8 km/sec system projected to cost $20–30 billion. For a description of these three alternative options, see Arthur and Roy, *Alternatives for Boost-Phase Missile Defense*, pp. 21–30.

[63] For all three of these surface-based options, CBO assumed that the Defense Department would deploy 60 interceptor missiles in 10 mobile batteries by 2012 and buy three cargo ships for basing at sea. Ibid., p. 41.

> solid-fuel ICBMs, dependence on access to foreign bases, vulnerability to being attacked or to exhausting their supply of interceptors, and strategic responsiveness. Not surprisingly, the greatest differences exist between the space-based systems and the surface-based ones.

Among the most important advantages of space-based boost-phase defenses is that that there would always be at least one SBI or SBL orbiting within range of any potential ICBM launch site, while in the case of surface-based boost-phase interceptors some time (as well as the permission of a foreign government) might be needed to deploy the system to the theater of operation. On the other hand, once deployed, a surface-based boost-phase defense system might be capable of intercepting more ICBMs than a space-based system.[64] As with the SBI and SBL options discussed in this chapter, an attacker's use of countermeasures (e.g., deploying faster burning ICBM boosters and decoy boosters) would reduce—and possibly eliminate entirely—the already limited capabilities of the surface-based boost-phase ballistic missile defense options considered by CBO.

Airborne Kinetic-Energy Interceptors

Another option for boost-phase ballistic missile defense, not evaluated by CBO, would be to use aircraft (rather than satellites) armed with either kinetic-energy interceptors or lasers. According to a 2002 study by Dean A. Wilkening,[65] the United States could, within the next decade, acquire and deploy an airborne boost-phase intercept (ABI) system,

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[64] Arthur and Roy, *Alternatives for Boost-Phase Missile Defense,* p. xviii. For example, even if the technology worked perfectly and no other countermeasures were used, the SBI constellations included in the CBO report would (as discussed earlier in this chapter) be capable of intercepting only one ICBM if the attacker salvo-launched its ICBMs from a single location and the launches were timed to occur during a (predicable) interval in which only two SBIs would be within range. By contrast, assuming that gaining access to foreign bases in a timely fashion was not a problem, under each surface-based boost-phase defense option considered by CBO, at least one, and as many as ten batteries—each consisting of six ready-to-fire interceptors—would always be within range of any possible launch sites in North Korea or Iran. Thus, assuming the technology worked perfectly and no other countermeasures were used, each of these surface-based options would be capable of intercepting a salvo consisting of from three to as many as 30 ICBMs (assuming two interceptors would be launched against each ICBM).

[65] Dean A. Wilkening, "Airborne Boost-Phase Ballistic Missile Defense," *Science and Global Security*, 12:1–67, 2004.

consisting of hundreds of kinetic-energy interceptors carried aboard aircraft. Specifically, the system would include 700 ABI missiles (including spares) and enough aircraft launch platforms to cover three defended areas, over North Korea or Iran, 24 hours a day, with a sufficient number of ABIs to handle the salvo launch of up to 20 liquid fuel ICBMs, or shorter-range ballistic missiles.[66]

Wilkening argues that this system would have a significant capability even against solid fuel ICBMs. However, because the airborne interceptors would have a much shorter range against solid fuel ICBMs (due to their shorter burn times), he acknowledges that maintaining a similar level of effectiveness would require the aircraft carrying the kill vehicles to move up to, or possibly over, North Korean or Iranian airspace.[67] Once again, as with the other boost-phase options discussed in this report, this system's effectiveness could also be significantly reduced through the use of various countermeasures such as faster burning ICBM boosters and decoy boosters.

Wilkening estimates that procurement costs for this system would amount to some $11–18 billion, including about $2 billion for the ABI missiles and $9–15 billion for fighter or other aircraft launch platforms.[68] He does not provide an estimate of the cost of developing the ABI missile, or operating the system over its lifetime. A reasonable estimate is that development costs would amount to some $5 billion, bringing total acquisition costs to $16–23 billion.[69] Operating expenses could more than double these costs, assuming a 20-year life for the system.

Airborne Lasers

Another ballistic missile defense option, and one that the United States is currently pursuing, is the airborne laser (ABL). The ABL system the Air Force is now developing is intended primarily for use against short- and medium-range ballistic missiles. As planned, this system would consist of

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66 Ibid., p. 45.
67 Ibid., pp. 40–42.
68 Ibid., p. 45.
69 This estimate assumes that development costs for the ABI would be less than they would be for the slower of the two space-based boost-phase interceptors described by CBO ($8 billion), but more than for the air-launched miniature vehicle (ALMV), an air-launched ASAT weapon that was projected to cost $2–3 billion to develop before it was cancelled in the mid 1980s.

seven modified 747 aircraft, each equipped with a COIL laser. The precise specifications of the system are classified, but it will reportedly have a power output of about 3 megawatts and be directed by a 1.5 meter mirror.[70] Although intended primarily for use against shorter-range ballistic missiles, the ABL would also have some capability against ICBMs.

According to the 2003 APS study of boost-phase ballistic missile defenses, the ABL would have a useful range against liquid fuel ICBMs of about 600 km, and would be capable of protecting the United States from a limited ICBM attack launched from North Korea, but incapable of defending against a similar attack from Iran, unless the United States could station ABLs over the Caspian Sea or Turkmenistan.[71] However, the ABL's range against solid fuel ICBMs would be only about 300 km, insufficient to protect the United States from an ICBM launched from either North Korea or Iran.[72] Moreover, as with other boost-phase ballistic missile defense systems, even where individual ICBMs could be successfully intercepted, salvo launches could prove difficult to handle. As the APS study notes, multiple ABLs might need to be deployed to defend against even a moderate number of multiple launches.[73]

In addition, although—in contrast to the HF lasers discussed earlier for use with the SBL—on a clear day a COIL laser can penetrate the atmosphere relatively effectively, the range of such lasers can be dramatically reduced by cloud cover. The typical operating altitude of the ABL is projected to be about 12 km. But at that altitude clouds frequently exist. And even at 15 km, which may be close to the ceiling for a fully-loaded ABL, clouds typically exist about 10 percent of the time.[74] This raises questions about the fraction of the time a deployed ABL would be capable of engaging targets. In addition, the ABL would be vulnerable to most of the same countermeasures discussed with regard to the SBL.

The ABL program has suffered serious technical and other problems throughout its development history. Among other things, the ABL has not been able to meet its weight goals or schedule. Likewise, the program's

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70 APS, *Boost-Phase Intercept Systems for National Missile Defense,* p. S299.
71 Ibid., p. xxix.
72 Ibid., p. xxix.
73 Ibid., p. S143.
74 The extent of cloud cover varies depending on location and season. This figure represents the average for the earth's mid latitudes. Ibid., p. S340.

estimated cost has increased substantially over the past decade-and-a-half.[75] As such, it is unclear whether, or at least when, the ABL will be deployed and become operational. The problems encountered in the development of the ABL also underscore the seriousness of the—likely substantially greater—challenges that would have to be overcome in order to develop and deploy an effective SBL system.[76]

At present, acquisition costs for the ABL program are projected to be some $15 billion, including procurement costs of about $1.5 billion for each of the seven aircraft.[77] As in the case of an ABI system, operating costs could substantially increase the total cost of the ABL program over its lifetime.

Surface-Based Midcourse Kinetic-Energy Interceptors

All of the preceding terrestrial-based ballistic missile defense systems, at present, represent *potential* capabilities. However, the United States already possesses a surface-based midcourse ballistic missile defense system. In December 2005, the United States fielded eight ground-based interceptors at Fort Greely, Alaska. By the end of 2007, DoD is projected to have 21 ground-based interceptors deployed in Alaska and three more at a second site in California, as well as 21 (modified Standard missile) interceptors deployed aboard 10 Aegis cruisers and destroyers.[78]

It is impossible to estimate how much it will cost to complete this surface-based missile defense architecture, since its ultimate size and configuration has not yet be defined. In 2002, in the same study in which it analyzed the boost-phase SBL constellation discussed earlier, CBO provided an assessment of ground- and sea-based midcourse ballistic missile defenses. CBO estimated that a limited ground-based system, consisting of 100 interceptors, would cost $18–21 billion to acquire and, once fully

75 Christopher Bolcom, "Airborne Laser (ABL): Issues for Congress," *CRS*, October 22, 2003, pp. 5–8.

76 Among other things, an SBL would be more difficult to maintain, refuel and repair. Weight issues would also be a much more serious concern, given the high cost of lifting payloads into space.

77 CBO, *Budget Options* (Washington, DC: Government Printing Office, February 2007), p. 15.

78 Missile Defense Agency, "Missile Defense Agency Fiscal Year 2008 Budget Estimates Overview," January 31, 2007, p. 7.

deployed, have annual operating costs of some $700 million.[79] This implies 20-year lifecycle costs for the system of about $32–34 billion.

According to CBO, this ground-based system might be capable of intercepting a "few tens" of warheads, if the attacker used only simple countermeasures.[80] If so, this system would appear to be more effective than any of the SBI and SBL constellations considered above. On the other hand, it is not clear that such a system could defeat even relatively simple countermeasures. Among the most difficult challenges confronting any midcourse defense is the task of discriminating between warheads and decoys released from an ICBM. Some critics argue that even relatively simple decoys, such as light-weight aluminized mylar balloons (which, outside the atmosphere would travel at the same speed and on the same trajectories as real, much heavier, warheads), if released in sufficient numbers, could overwhelm a midcourse defense system. Although various solutions have been proposed for improving discrimination capabilities, it is by no means clear that those solutions will prove feasible or effective.[81]

In its 2002 study, CBO also considered a sea-based midcourse ballistic missile defense system. It estimated that a sea-based system consisting of seven-to-nine Aegis destroyers armed with 35 missile interceptors each, and supported by a variety of ground- and space-based sensors, would cost $43–57 billion to acquire, and have annual operating cost of some $1–1.1 billion.[82] This suggests 20-year lifecycle costs ranging from $64 to $80 billion. CBO did not discuss how effective such a system might be. However, since it would rely on much of the same technology as the ground-based system considered by CBO and would face the same challenges inherent in midcourse defense (e.g., decoy discrimination), it would presumably have a roughly comparable level of effectiveness.

While these estimates provide some indication of how much a surface-based midcourse ballistic missile defense system might cost to acquire and support, it is important to remember that these are estimates of illustrative systems, made some five years ago. It is unclear to what extent they are consistent with, or differ from, current plans for these kinds of defenses. They may overstate the cost of completing the acquisition of these systems,

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79 CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 9.

80 Ibid., p. 8.

81 OTA, *Ballistic Missile Defense Technologies*, p. 171.

82 CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 16.

among other things, because some of the costs included in CBO's estimates (especially for development) have already been incurred and covered over the past five years.[83] On the other hand, they may understate some costs. The United States could, for example, ultimately decide to construct even more expansive ground- and sea-based midcourse defenses than those described above, resulting in substantially higher costs.[84]

Chapter Summary and Conclusions

The analysis in this chapter suggests that an SBI constellation intended for the boost-phase ballistic missile defense mission would have 20-year lifecycle costs of some $29–290 billion, with the lower-end estimate requiring a technological leap in kill vehicle miniaturization. The technological uncertainty and risk associated with developing an SBL system for this mission is far greater. Indeed, it may be doubtful that, even absent budgetary constraints, such a system could be developed within the time frame considered in this report. But assuming those hurdles could be overcome eventually, such a system might have costs ranging from $128–196 billion.

Despite these high costs, it appears likely that neither of these systems would have more than, at best, a very modest capability, even in the absence of countermeasures. In the case of the SBI constellations considered in this chapter, if the attacker prudently timed and salvo-launched its attack, only a single ICBM could be intercepted (assuming, consistent with current MDA doctrine, that two interceptors would be launched against each booster)—even if the technology worked perfectly. In the case of the SBL constellations described above, perhaps a half-dozen ICBMs could be intercepted in the event of such an attack.

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83 In addition, since the ground- and sea-based midcourse ballistic missile defense systems described in the two CBO options discussed here would make use of some of the same technologies and systems, simply adding together the two cost estimates would overstate the cost of acquiring and supporting both systems.

84 Some idea of how much increasing the size and technological sophistication of a surface-based midcourse ballistic missile defense system could result in higher costs can be gained by considering two other options included in CBO's 2002 study. The first of these options would, among other things, expand the ground-based midcourse system from 100 to 250 interceptors, while the second would increase the size of the system to 375 interceptors located at three sites. The 20-year life cycle costs of these two options would be about $90–102 billion and $99–113 billion, respectively. CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 9.

Given the fact that, for a country that has already developed and deployed a single ICBM the production costs of additional ICBMs would likely be in only the tens of millions of dollars, a simple cost-exchange analysis strongly suggests that the acquisition of such defenses would not be a cost-effective option for the United States—at least over the next two decades. Moreover, if the attacker employs even relatively simple countermeasures, the effectiveness of these systems could be substantially further reduced, or eliminated entirely. Furthermore, the cost-exchange ratio appears to be so lopsided in favor of the attacker that this may be a case where the United States cannot prevail by simply outspending its opponent.

Nor are budgetary costs the only obstacle standing in the way of space-based ballistic missile defenses. Especially in the case of an SBL defense, successfully developing a system with even very modest capabilities would require significant technological advances that may not be achievable over the next two decades.

This chapter also discussed a half-dozen alternative surface-based and airborne ballistic missile defense systems, including several kinds of systems the United States already operates or is acquiring. The estimated life-cycle cost of these systems ranged from about $15 billion to $80 billion. This is generally less, and in most cases far less, than the costs projected for the SBI and, especially, the SBL ballistic missile defense systems considered in this chapter.

Despite the generally lower cost of these terrestrial-based options, unless they are determined to be, not only less costly, but also substantially more effective and less vulnerable to countermeasures than the space-based SBI and SBL systems considered in this report, they may not represent cost-effective investments for the United States either. In other words, it is possible that a cost-exchange analysis of these terrestrial-based options for ballistic missile defense would also reveal a significant—and perhaps insurmountable—advantage resting with the offense. In that case, neither space-based nor terrestrial-based ballistic missile defense programs would, at least for the foreseeable future, appear to hold much promise in terms of cost-effectiveness. On the other hand, it is possible that, while space-based defenses may not be cost-effective, one or more of the terrestrial-based alternatives discussed in this chapter would represent a cost-effective investment.

Chapter 2: Space-Based Systems for Attacking Terrestrial Targets

A space-based system designed to attack terrestrial (ground- and sea-based, or airborne) targets would be easier and less costly to deploy than an even a marginally effective space-based ballistic missile defense system. However, even in this case, some significant technological issues would need to be resolved and the costs could be substantial. Moreover, as in the case of the ballistic missile defense mission, ground- and sea-based systems (e.g., conventionally armed ICBMs and SLBMs), or airborne systems (e.g., bombers or other aircraft) would generally appear to be more cost-effective, and less technologically risky, than space-based systems.

As with space-based ballistic missile defense systems, at the most basic level there are essentially two different kinds of weapons that could be used to strike terrestrial targets from space: weapons that rely on physically hitting their targets (i.e., kinetic-energy weapons) and lasers. And, again as with space-based ballistic missile defense systems, the technology for the former is substantially more mature than it is for the latter, and the costs for such a system are likely to be significantly lower than for a space-based laser.

Advocates of using space-based weapons to attack terrestrial targets focus on the ability of such weapons to conduct “prompt” strikes against targets located anywhere in the world. In essence, the theoretical advantages that might accrue to space-based systems used for this mission resemble those that accrue to space-based weapons used for boost-phase ballistic missile defense. Unfortunately, from a cost-effectiveness standpoint, some of the same limitations likewise apply. In particular, such a system would also be affected by the absentee problem that contributes substantially to the high cost of space-based boost-phase ballistic missile defense constellations.

Mass-to-Earth Weapons

In recent years, the focus of most discussions about space-based prompt strike capabilities has been on "mass-to-earth" weapons that must physically hit their targets. These include both weapons armed with conventional (e.g., high explosive) munitions and kinetic-energy weapons that use their own mass and very high velocity for destructive effect.

In a 2006 study, CBO assessed a range of alternative long-range strike systems, including a space-based weapon that would launch maneuverable re-entry vehicles (known as a common aero vehicles, or CAVs) carrying conventional munitions against targets on earth.[85] Under the option described by CBO, each CAV would carry a 1,000-pound warhead or an equivalent payload of submunitions. Each CAV would be capable of gliding and maneuvering for up to several thousand miles during reentry, giving even CAVs based in low-earth orbit relatively large coverage footprints.

In specifying the system's performance characteristics, CBO assumed that the constellation of space-based CAVs would have to be capable of striking targets located anywhere on earth within one hour.[86] This would give it a response time comparable to that of a CAV-equipped ICBM (an option discussed latter in this chapter). CBO calculated that a constellation of five satellites orbiting at an altitude of about 500 km would allow for such coverage. In order to allow multiple targets to be hit, or for individual targets to be hit multiple times, each of these satellites was assumed to carry eight CAVs.

According to CBO, this constellation would be capable of striking any target on earth—that could be detected, identified and, if necessary, tracked—within 15 minutes to one hour of a decision to "de-orbit" and launch the CAVs. The response time would depend on how close the nearest CAV satellite was to the intended target at the time a decision was made to strike. However, a minimum of 15 minutes would be required to strike even the closest target because of the time needed to de-orbit the satellite (the orbiting CAV would have to fire its retro-rocket to slow itself to suborbital speed) and, subsequently, for the CAV to reenter the atmosphere.[87]

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85 Robie Samanta Roy and David Arthur, *Alternatives for Long-Range Ground Attack* (Washington, D.C: CBO, March 2006).

86 Ibid., p. 19.

87 Ibid., p. 11.

CBO estimated that developing and procuring this constellation of CAV satellites would cost $12 billion[88] (see Figure 2). This includes the cost of acquiring the initial five-satellite constellation (plus 40 CAVs) as well as the cost of acquiring another 11 satellites (and 80 CAVs) to be used as replacements and spares over the system's presumed 30 year life. It does not, however, include operating costs.

Another option would be to acquire a space-based mass-to-earth weapon designed to kill through high-velocity impact. In this case, rather than launching CAVs armed with conventional (e.g., high explosive) munitions or subminitions from space, which could maneuver and glide for up to several thousand miles during reentry before hitting their targets, long-rod penetrators—made out of high-density material, such as tungsten—would be launched, at very steep angles (to maximize velocity), from space.[89]

According to a 2003 RAND report, a constellation of roughly 35–65 space-based long-rod penetrators in orbit at 4,000-8,000 km could achieve global coverage and a maximum response time of about one hour[90]—i.e., provide roughly the same global coverage and response time possible with the five-satellite low-earth orbit CAV constellation described earlier.

The number of space-based long-rod penetrators needed to achieve global coverage could be reduced if the satellites were based in higher altitude orbits—since, as altitude increases, the size of the footprint capable of being attacked at steep angles grows. But the inevitable tradeoff is that as altitude increases, the response time also grows, since the long-rod penetrator must fall further to reach its target. An absentee ratio of 5-to-1 could be achieved if the orbit was increased to 32,000 km (geosynchronous orbit). But this five-satellite constellation would have a response time of 2–3 hours.[91]

RAND did not provide a cost estimate for the space-based long-rod penetrator constellations described above. It seems likely, however, that a constellation of space-based long-rod penetrators designed to

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[88] Ibid., p. 50.

[89] Up to a point, high velocity improves the effectiveness of long-rod penetrators against targets such as hardened or deeply buried bunkers. However, if its velocity becomes too high the rod may begin to vaporize, reducing its ability to penetrate to or through the target.

[90] Preston et al, *Space Weapons, Earth Wars*, p. 155.

[91] Ibid., p. 155.

provide roughly the same capabilities as the constellation of five space-based CAV satellites described earlier would have costs of roughly the same magnitude.

A reasonable estimate is that development costs for the space-based long-rod penetrator would be comparable to the $4 billion projected by CBO for the space-based CAV. Both would represent new, never-before-deployed, weapon systems that would require great accuracy as well as advances, among other things, in reentry vehicle technology. Assuming that procurement costs would be proportional to the mass of the satellite's weapon's payload, each (100-kilogram) long-rod penetrator would be projected to cost about 22 percent as much as a single CAV (with its 450-kilogram munitions payload). However, some procurement costs—such as those related to the weapon's guidance system—would presumably not be affected by the mass of the weapon itself. As such, as a very rough approximation, it might be reasonable to assume that each space-based long-rod penetrator would cost about 30 percent as much as a space-based CAV to procure. This implies total procurement costs for a constellation of 35–65 space-based long-rod penetrators of some $2–4 billion.[92]

Taken together, these estimates of development and procurement costs suggest that total acquisition costs for such a system would amount to some $6–8 billion. However, this may substantially understate the cost of such a system. According to another estimate, deploying a constellation of forty 100-kilogram long-rod penetrators (plus the associated propulsion systems that would be used to power their high-speed descents to earth) would have *launch costs alone* of some $9 billion.[93] This suggests that the total acquisition cost for such a system would be over $13 billion,[94] making it roughly as expensive as CBO's space-based CAV option.

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[92] CBO projects total procurement costs of $8 billion for the space-based CAV. The procurement cost estimate assumes the purchase of a total of 128 CAVs and 16 CAV satellites (necessary to maintain, over 30 years, a constellation of five CAV satellites—each armed with eight CAVs). Roy and Arthur, *Alternatives for Long-Range Ground-Attack Systems*, p. 49. Assuming that the unit procurement costs for the space-based long-rod penetrator would be equivalent to 30 percent of the space-based CAV's costs, and that a similar ratio of deployed-to-replacement and spare systems would be required, total procurement costs would be projected to be $2 billion to $4 billion.

[93] DeBlois et al, "Space Weapons: Crossing the US Rubicon," p. 70. As noted earlier, in the case of space-based weapons, estimates of procurement costs provided in this report generally include the costs associated with launching the weapons into orbit.

[94] This figure includes $4 billion in development costs plus $9 billion in launch costs. Additional costs would be incurred in actually producing the long-rod penetrators (and associated equipment) that would be lifted into orbit.

Figure 2: Cost Estimates for Illustrative Prompt-Strike Systems
(in 2007 dollars)

System	Cost*
Space-Based	
Space-Based CAV	$12 billion
Space-Based Long-Rod Penetrators	$6–13 billion-plus
Space-Based Laser (SBL)	Several billion (or less) to $196 billion**
Terrestrial-Based	
Surface-Based Medium-Range CAV	$3.8 billion
Surface-Based Long-Range CAV	$4.1 billion
Conventional Trident II	$500 million^

* Estimates generally include development and procurement cost associated with acquiring the system and (once fully deployed) operating it for 30 years.
** Range reflects difference between SBL constellations designed to conduct non-lethal/harassing attacks (low estimate) versus lethal/destructive attacks (high estimate).
^ Includes only initial acquisition costs.

Space-Based Lasers

A constellation of SBLs could also be used to attack terrestrial targets. But only some types of lasers could be used for this task—those capable of penetrating the earth's atmosphere—and the class of targets that could be disabled or destroyed by these lasers is relatively narrow. Moreover, since no lasers are capable of penetrating cloud cover, such a system would often be incapable of attacking even these targets. This is a potentially serious limitation because, on average, 30–40 percent of the Earth's surface is under cloud cover.[95] In general, because the technology is less mature, developing and deploying an SBL capable of effectively attacking terrestrial targets would be more difficult, risky and costly than acquiring a space-based kinetic-energy strike system. However, the cost and complexity of developing and deploying such an SBL constellation could vary substantially depending on the precise goals set for it.

As note earlier, some types of lasers (e.g., the HF laser) cannot penetrate the earth's atmosphere below about 15 km (about 50,000 feet), while other lasers, such as deuterium-fluoride (DF) and COIL lasers can penetrate much deeper through the atmosphere if adaptive optics are

95 DeBlois et al, "Space Weapons: Crossing the US Rubicon," p. 73.

used to compensate for atmospheric turbulence—which would otherwise dissipate the beam. Even these lasers, however, may have difficulty reaching targets on the Earth's surface, depending, in part, on the angle at which the laser's beam is directed to its target (which, in turn, affects the distance the beam must travel through the atmosphere).[96]

In theory, a laser able to penetrate the Earth's atmosphere could be used to attack aircraft and cruise missiles in flight, above-ground fuel storage tanks, fuel trucks, missile launch and transport vehicles, and other thin-skinned or flammable targets.[97] A laser would have essentially no capability against common military targets such as bunkers, armored vehicles or buildings.[98]

Since aircraft and cruise missiles in flight, by definition, operate at higher altitudes, space-based lasers would face less interference from atmospheric turbulence and cloud cover when targeting these systems than when attempting to attack surface targets. However, especially compared to fixed ground targets, detecting, tracking, identifying and targeting aircraft in flight with an SBL would be very difficult.[99]

According to the 2002 RAND report, to the extent that relatively thin-skinned or flammable targets are "vulnerable to the kind of surface-heating damage that a laser can inflict, they should require amounts of laser fuel to engage these targets that are similar to those required for a missile target."[100] This implies that at comparable ranges, effectively engaging these kinds of terrestrial targets would also require SBLs equipped with lasers and mirrors roughly as capable as those needed for boost-phase ballistic missile defense.

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96 The laser of an SBL attempting to attack a target directly below it would only have travel through about 15 km of atmosphere. In all other cases, however, the slant range through the atmosphere that the beam would have to travel would be greater.

97 Preston et al, *Space Weapons, Earth Wars,* p. 34.

98 DeBlois et al, "Space Weapons: Crossing the US Rubicon," p. 72.

99 Perhaps the most difficult part of the anti-aircraft mission would be finding targets. Detecting an aircraft against a warm and cluttered Earth background is harder than spotting a satellite against the cold and relatively empty background of space. Cruise missiles, being smaller, would be even harder to find; the application of stealth technology would complicate the task still further. OTA, *Ballistic Missile Defense Technologies,* p. 191.

100 Preston et al, *Space Weapons, Earth Wars,* p. 34.

These considerations suggest that an SBL designed to attack a small number of high-value terrestrial targets might cost roughly the same amount as one intended for ballistic missile defense. If the goal was to have a constellation of SBLs capable of striking anywhere on Earth within seconds or tens of seconds of a decision to attack, an SBL system designed for terrestrial attack might also closely resemble an SBL system designed for missile defense in terms of constellation size.[101] Taken together, this suggests that the cost of acquiring and supporting the former system would probably be similar to the cost of fielding the latter—i.e., on the order of $128 to $196 billion. Costs would be lower if a smaller constellation was deployed. However, the smaller the constellation, the less likely it would be that, at any given time, targets of interest would be within range of such a system.

Compared to either of the mass-to-earth weapons described earlier, in clear weather and assuming there was a target within range, an SBL would have a shorter response time—measured, at least in some cases, in perhaps seconds or tens of seconds.[102] On the other hand, cloud cover could render it completely ineffective. Put another way, because of cloud cover, the SBL's response time might frequently be measured in hours or even days—making it much *less* responsive than mass-to-earth weapons. Moreover, it would, at best, be capable of effectively engaging only a relatively narrow class of targets. In most cases, each SBL would, like the mass-to-earth weapons described earlier, also presumably be capable of attacking only a relatively small number of targets.[103]

The use of simple countermeasures, such as smoke screens, ablative cork coatings, or pools of water, could also significantly degrade the effectiveness of lasers designed for attacking terrestrial targets. As noted in the preceding chapter's discussion of countermeasures for SBLs intended

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[101] This conclusion is also consistent with the view that, in the case of an SBL system intended to attack terrestrial targets, "continuously covering strategically important regions (in clear weather) would require a constellation of several dozen lasers." Dubois et al, "Space Weapons: Crossing the US Rubicon," p. 72.

[102] While the laser energy could reach its target nearly instantaneously, it would take some time to acquire the target and generate a firing solution.

[103] The ABL, which is expected to have enough laser fuel to engage some 20 ballistic missiles (O'Hanlon, *Neither Star Wars Nor Sanctuary,* p. 74), may be suggestive of the number of comparably-hard terrestrial targets a single SBL could engage. However, in one case—an SBL architecture consisting of a ground-based laser(s) and a number of relay mirrors—such a system would presumably be able to fire against a much larger number of targets (since the ground-based laser could have a much greater fuel supply that could be easily replenished).

for boost-phase ballistic missile defense, the use a three-centimeter-thick coating of cork, for example, could increase dramatically the laser dwell time needed to destroy a typical target. In turn, since a chemical laser would use 2–3 kilograms per second of fuel per megawatt of laser power,[104] increasing the required dwell time from seconds to tens of seconds, or minutes, could greatly reduce the number of targets that could otherwise be engaged.

If, instead of conducting lethal attacks against the relatively narrow class of terrestrial targets described above, the goal was to acquire an SBL system capable of attacking an even narrower class of targets through non-lethal and indirect means—such as the illuminating or simulating fluorescence in aircraft canopy materials to degrade the pilot's view out of the cockpit[105]—it might be possible to keep costs lower. Just how much lower, however, would depend on how much less capable the system was designed to be.

As a very rough first approximation, it might be reasonable to assume that such a system would cost at least as much to develop and procure as an SBL designed to dazzle or blind certain satellite sensors. As will be discussed in more detail in Chapter 3, for a variety of reasons, an SBL designed to kill or disable enemy satellites could be made much less capable than one intended for boost-phase ballistic missile defense. And an SBL designed to interfere with a satellite's sensor, rather than destroy the satellite, could be even smaller and less powerful—and, thus, less costly to acquire. Although it is difficult to project the costs of developing and deploying this kind of system with much confidence, it is possible that a constellation of 24 such satellites would have 20-year lifecycle costs of as little as several billion dollars, or perhaps even less.[106]

Costs would be lower if a smaller constellation was deployed. However, the smaller the constellation, the less likely it would be that, at any given time, targets of interest would be within range of such a system. Moreover, it might be more difficult (and perhaps far more difficult) to detect, identify and track some high-value terrestrial targets that would, in theory, be vulnerable to relatively weak laser attacks, such as aircraft, than it would be to effectively detect and target most low-earth orbit

[104] Preston et al, *Space Weapons, Earth Wars*, p. 29.
[105] Ibid., p. 34.
[106] See the discussion of SBL ASATs in Chapter 3 for a discussion of how this cost estimate was derived.

satellites. As such, the cost of acquiring an SBL system designed for non-lethal attacks against terrestrial targets might be greater than for an SBL system optimized for dazzling and blinding satellites.

Alternative Terrestrial-Based Strike Systems

In its 2006 study, *Alternatives for Long-Range Ground Attack*, CBO also considered a range of terrestrial-based long-range strike systems. These consisted of five different aircraft options and two options involving the use of medium-range or long-range ballistic missiles armed with CAVs.[107] For missions requiring sustained firepower, such as would be needed to conduct major combat operations similar to the 1991 Gulf War, the war in Kosovo, or, more recently, the initial phases of Operations Enduring Freedom or Iraqi Freedom, space-based CAVs represent a very unattractive option. This is because they have relatively high unit costs and, unlike bombers which can fly multiple sorties (i.e., combat missions), each CAV could only be used once.

Just how ill-suited space-based CAVs are for missions requiring sustained firepower can be seen in a simple illustration. According to CBO, the United States could buy a fleet of 150 long-range supersonic bombers for about $210 billion.[108] A fleet of this size would support an operational force of about 100 aircraft to be used in combat. Such a force would be capable of delivering a payload equivalent of about 2,100 Joint Direct Attack Munitions (JDAMs)[109] per day to a range of 7,000 nautical miles (nm).[110] The procurement costs of a similar number of space-based CAVs would also amount to about $210 billion. But this bomber force could fly many missions—perhaps dozens or even hundreds, with the precise number depending on the effectiveness of enemy air defenses and other factors. By contrast, this $210 billion space-based CAV constellation would have only a single-shot capability.[111]

107 Roy and Arthur, *Alternatives for Long-Range Ground Attack,* pp.11–14.

108 Ibid., p. xv.

109 The satellite-guided JDAM is presently the most widely used PGM in the US military.

110 Roy and Arthur, *Alternatives for Long-Range Ground Attack,* p. 33.

111 Over the near-to-intermediate term, the cost advantage accruing to bomber forces may be even greater than these figures suggest. This is because the United States already possesses a fleet of some 150 bombers (which, in effect, represent sunk costs).

Moreover, the US military has expended at least 6,700, and as many as 18,400, precision-guided munitions (PGMs) in each of the last four major conflicts in which it has been involved.[112] Thus, a ($210 billion) 2,100-JDAM capability would probably not come close to meeting US requirements for sustained firepower in a future major military conflict.

As a result of this calculus, space-based CAVs would likely prove cost-effective only if used against a small number of high value targets requiring extremely prompt strike over global distances. Against such targets, space-based CAVs could have a dramatic advantage over long-range aircraft. As noted earlier, a space-based CAV constellation consisting of five satellites would have a maximum response time of one hour. By contrast, the aircraft fleets evaluated by CBO would have response times measured in several to many hours when operating over very long distances. For example, a supersonic bomber (with a maximum speed of Mach 2.4) flying 5,000 nm (e.g., the distance from Guam to Afghanistan) would take 4 hours to reach its target, while a subsonic bomber flying over the same distance would take 10 hours.[113]

If aircraft could be based within the theater of conflict, maximum response times would dramatically decline. At 2,500 nm, for example, the response time of a supersonic aircraft would drop to about 1.8 hours, while the response time of a subsonic bomber would fall to about 5 hours.[114] If aircraft were already airborne and loitering in the area, or possibly on alert at a base located within 500 nm (for subsonic aircraft) to 1,500 nm (for supersonic aircraft) of the intended target, they might be able to match—or possibly even exceed—the (one hour maximum) response time of a space-based CAV.[115]

Surface-based ballistic missiles equipped with CAVs would have comparable response times to space-based CAVs. CBO considered two such options in its 2006 study of long-range ground-attack capabilities. Under one option, a ballistic missile small enough to fit in a mobile launcher would be developed, and each of these missiles would be armed

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[112] These conflicts include the 1991 Gulf War, the 1999 war in Kosovo, and the initial phases of the wars in Afghanistan and Iraq. Steven M. Kosiak, "Matching Resources With Requirements: Options for Modernizing the US Air Force" (Washington, DC: Center for Strategic and Budgetary Assessments, August 2004), p. 53.

[113] Roy and Arthur, *Alternatives for Long-Range Ground Attack*, p. 20.

[114] Derived from Figure 3-3, Ibid., p. 19.

[115] Ibid.

with a single CAV.[116] These missiles would be used to boost the CAV above the earth's atmosphere. The maximum range of the CAV would be about 3,240 nm. The CBO option assumes that 24 two-missile medium-range CAV batteries would be acquired, 20 of which would be for operational use and four for spares.[117] The batteries would be light enough to be easily transported by air to forward areas.

Assuming a medium-range CAV battery was deployed within range of the intended target, the response time for this system would range from as little as 10 minutes to as much 30 minutes.[118] Thus, under some circumstances, at least, this system would have a slightly shorter response time than a space-based CAV. On the other hand, if one of these batteries was not forward-based within range of the intended target, the response time for this system might be measured in hours or even days.

In the case of CBO's long-range surface-based CAV option, the CAV would be placed atop an ICBM. Specifically, CBO assumes that 20 Peacekeeper ICBMs (recently retired from service) would be used, with each missile capable of carrying two CAVs, and attacking targets over essentially global ranges. The 20 missiles would be divided into two groups of 10 missiles (20 CAVs) each, and deployed on both coasts of the United States (at Cape Canaveral Air Force Station in Florida and Vandenberg Air Force Base in California). Like a space-based CAV constellation, this missile force would be capable of providing global coverage. Response time for this system would range from about 30 minutes to an hour, depending on the distance to the target.

According to CBO, the surface-based medium-range CAV option described above would have 30-year lifecycle costs of $3.8 billion, while the surface-based long-range CAV option would have 30-year lifecycle costs of $4.1 billion.[119]

As part of the 2006 Quadrennial Defense Review (QDR), DoD announced plans to convert some 24 Trident II SLBMs to carry conventional warheads. Under this plan, each of the 12 Ohio-class Trident ballistic missile submarines (SSBNs) normally operationally deployed would be armed

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116 Ibid., p. 13.
117 Ibid., p. 14.
118 Ibid,, p. 22.
119 Ibid., p. 50.

with two conventionally-armed missiles.[120] Rather than carrying a CAV, these missiles would reportedly be equipped with conventional warheads optimized for striking either deeply buried or surface targets.[121] Such a force would apparently have capabilities roughly similar to those provided by CBO's medium-range and long-range surface-based CAV options.

These missiles would have a flight time of as little as 12 minutes against targets located relatively close to the submarine's launch position[122]—comparable to the minimum response time of CBO's medium-range surface-based CAV option. The conventionally-armed Trident II missile would, however, have a maximum range of about 6,000 miles—nearly twice that of CBO's medium-range surfaced-based CAV option.[123] Another operational advantage of this system is that its effectiveness would not be dependent on the ability to gain access to forward bases, as would be the case with the medium-range CAV option.

On the other hand, assigning SSBNs a conventional prompt global-strike mission could, at least in some circumstances, interfere with or compromise the Trident fleet's primary strategic (nuclear) deterrent mission. A more serious problem may be that there would be no way for another country that detected the launch of such a missile to know for certain that it was conventionally-armed, rather than nuclear-armed. This has raised concerns that the use of conventionally-armed Trident II missiles against a nuclear-armed state could inadvertently escalate a conflict to the nuclear level.[124]

DoD estimates that developing and procuring conventional warheads for 24 Trident II missiles would cost about $500 million over the next five years.[125] Citing concerns about the potential for nuclear escalation,

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[120] The US strategic nuclear deterrent includes a total of 14 Trident SSBNs. However, at any particular time, two of these submarines are normally in port undergoing overhaul. DoD plans to retain this force structure for the foreseeable future.

[121] Elaine M. Grossman, "DoD Defends New Sub-Launched Missiles," *InsideDefense.Com*, March 10, 2006.

[122] Ibid.

[123] Ibid.

[124] Similar concerns have been raised about the option of arming Peacekeeper ICBMs with conventional warheads. However, in this case the risk of inadvertent escalation might be reduced somewhat by, as proposed in the CBO Peacekeeper option, locating the launch sites for conventionally-armed ICBMs away from the bases at which US nuclear-armed ICBMs are located.

[125] Grossman, "DoD Defends New Sub-Launched Missiles."

among other things, Congress rejected DoD's fiscal year 2007 request for funding to begin implementing conventional modifications of Trident II missiles. However, the Navy is continuing with related research efforts.

Chapter Summary and Conclusions

A space-based kinetic-energy weapon designed to strike terrestrial targets could be developed and deployed for substantially less than it would cost to acquire a space-based kinetic-energy weapon (i.e., an SBI) designed for boost-phase ballistic missile defense—among other things, because the size of the required constellation would be much smaller. However, such a system would still be significantly more expensive than comparably-effective surfaced-based alternative prompt-strike systems—such as a force of CAV-equipped ICBMs or SLBMs.

In general, SBLs would appear to be even less cost-effective in this role than space-based kinetic-energy systems. An SBL constellation designed to strike terrestrial-based targets might cost as much as one intended for boost-phase ballistic missile defense, depending (among other things) on the desired response time (which would largely drive the size of the constellation required). Moreover, such a space-based system would be capable of attacking only a narrow class of relatively soft targets. An SBL system designed essentially to harass, rather than disable or destroy, an even smaller class of targets could be acquired at lower cost, but its capabilities would be much more limited.

It is also unclear how critical the prompt-strike mission is for the US military—whether carried out by space-based or terrestrial-based systems. And for targets not requiring prompt strike, aircraft equipped with PGMs would appear to represent a far more cost-effective option for the United States.

Taken together, these findings suggest that, at present, the prompt-strike mission does not provide a convincing rationale for developing and deploying space-based weapons. That said, in contrast to the case with space-based ballistic missile defense systems, it is much more difficult to dismiss space-based weapons designed to attack terrestrial targets on simple affordability and cost-effectiveness grounds.

For a variety of reasons—including the availability of comparably-effective and less expensive surface-based alternatives, as well as concerns about sparking, or at least accelerating, an arms race in space that would run counter to US interests—it may make little sense for the US military to acquire space-based weapons for the foreseeable future. However, developing and deploying a space-based CAV system, for example, would (at some $12 billion) certainly be affordable for the United States. And, in contrast to the case with space-based ballistic missile defenses (which may not only be less cost-effective than terrestrial-based alternative systems, but appear to fail the cost-effectiveness test when measured against an opponent's ability to overwhelm such a defense), a space-based prompt-strike system—even if not generally the *most* cost-effective approach—might still prove to be *a* cost-effective means of attacking some high-value targets.

Chapter 3: Space-Based Anti-Satellite Weapons

The United States and the rest of the world today rely on satellites to perform a wide variety of important functions. Altogether there are currently some 800 working satellites in orbit around the earth, including communication, navigation, reconnaissance, and weather satellites.[126] Of this total, roughly half are in low-earth orbit and half at higher altitudes.[127] Each year, scores of new satellites are launched into space, with the total value of these new satellites amounting to some $10 billion.[128] In recent years, roughly a third of all satellite launches have been conducted by the United States, with the remainder being split between the states of the former Soviet Union (especially Russia) and the rest of the world.[129] Satellites are used for both commercial and military purposes. The importance of satellites for the global economy, and especially developed economies, as well as certain military missions, has led to considerable interest in the ASAT mission, including space-based ASAT capabilities.

Overview

Like space-based prompt-strike weapons, space-based ASAT weapons would generally be easier and less costly to acquire and deploy than space-based ballistic missile defense systems, although precisely how

126 Union of Concerned Scientists, "Space Weapons Basics: What's in Space?" available at www.ucsusa.org/global_security/space_weapons/whats-in-space.html.

127 O'Hanlon, *Neither Star Wars Nor Sanctuary*, p. 38. Low-earth orbits extend out about 200 km to 5,000 km from the earth. Most satellites located out further from earth are in geosynchronous orbits (35,888 km).

128 Ibid.

129 Ibid.

much easier and less costly would depend on the specific system selected. This is because satellites (with their continuous, predictable orbits and sensitive sensors and other equipment) would generally be easier to detect and track, and (if effectively targeted) damage or destroy, than ballistic missiles. That said, the vulnerability of satellites could vary dramatically depending, among other things, on the nature of their mission, cost, complexity and orbital altitude.

Several countries have developed and tested dedicated terrestrial-based ASAT capabilities, including the United States, Russia and China. However, as far as is known based on unclassified sources, only Russia appears to currently possess a dedicated ASAT interceptor capability—a relatively primitive co-orbital system—and it is unclear whether this system is still active.[130] Notwithstanding persistent concerns, dating back to the early years of the Cold War, over an ASAT arms race, to date such a competition has largely been avoided.

The United States has by far the most sophisticated, effective and costly network of commercial satellites deployed in space. Likewise, the US military possesses the world's most effective and costly network of military satellites. As such, the United States may benefit more than any other country from the current absence of a serious ASAT competition. This has led some observers to argue that the United States should refrain from taking steps that might help ignite such a competition. Other observers have argued that such a competition is inevitable, and to some extent already underway, and that the United States needs to focus on ensuring that it wins this arms race (or at least stays ahead).

It does not appear (again, based on unclassified sources) that any country has, as yet, deployed a space-based ASAT capability. However, over the years, a number of different space-based ASAT options have been suggested. These can be divided into five basic alternatives.

- SBIs;
- Space mines (kinetic or explosive);
- SBLs;

[130] The United States maintained an operational direct ascent ASAT capability from 1963 to 1975. The system consisted of nuclear-armed Nike-Zeus missiles (1963–64) and Thor missiles (1965–75).

- Space-based jammers; and

- Space-based high-power microwaves.

Paralleling the approach used in the previous two chapters of this report, the first part of this chapter includes a brief discussion of various space-based ASAT options, while the second part discusses a range of terrestrial-based alternatives. Although, again paralleling the approach of past two chapters, this includes a discussion of the potential cost of each option, it is important to emphasize that the cost estimates provided in this chapter are extremely rough—and, in most cases, much less precise than the estimates provided in the two preceding chapters.

In the case of ballistic missile defense systems and (to a lesser extent) prompt strike systems, a number of estimates have been provided by CBO, DoD and others that can be used as a baseline from which to estimate the cost of a wider range of similar options. By contrast, there are very few publicly available cost estimates of ASAT capabilities. To make matters worse, there are also a wide variety of different systems and system architectures that might be used for the ASAT mission, making the lack of useful baseline estimates even more problematic. Thus, the cost estimates provided in this chapter, even more so than those included in the two preceding chapters, should be taken as only very rough, order-of-magnitude estimates.

It is also important to understand that, as in the previous two chapters, the cost estimates provided below generally assume little or no use of countermeasures. As with ballistic missile defense and prompt-strike systems, an adversary's use of (in some cases even relatively simple) countermeasures might, in fact, substantially (or even dramatically) reduce the effectiveness of many of these ASAT systems. Possible ASAT countermeasures include the use of satellite hardening, decoys, evasive maneuvering, and on-orbit or replenishment spares. To the extent that it may be possible to overcome these and other countermeasures, doing so could require the acquisition of much more capable (and costly) systems or system architectures than those described here. On the other hand, in some cases, cost-effective ASAT countermeasures may not be available.[131]

[131] See Chapter 4 for a discussion of various possible ASAT countermeasures.

SBI ASATs

An SBI designed for the ASAT mission would use essentially the same kill mechanism to destroy satellites that an SBI optimized for ballistic missile defense would use to intercept ballistic missiles. As in the former case, the SBI ASAT would be equipped with one or more high-speed kinetic-energy interceptors with which it would attempt to destroy or disable its target. The actual kill could be accomplished either through the use of a precision-guided warhead, or an explosive (or similar) warhead that would deploy a cloud of small fragments or pellets.[132]

Although it would operate in a similar way and make use of much of the same technology, an SBI ASAT would likely differ from an SBI designed for ballistic missile defense in a number of respects. For one thing, the SBI needed for a successful satellite intercept might be substantially smaller than one sized for ballistic missile defense. Such an interceptor would require less maneuverability for the homing process and for accelerating out of orbit.[133] In turn, this means the SBI's rocket motor would require less propellant, reducing the mass of the system. According to one estimate, because of the need for less maneuverability (and thus less rocket propellant), an SBI ASAT might (holding all else constant) require only about one-third the mass of an SBI designed for boost-phase intercept.[134]

Although an SBI ASAT could probably be made smaller than an SBI designed for ballistic missile defense, it would be capable of attacking targets over a much longer range than would an SBI designed for boost-phase ballistic missile defense. This is because it would not have to complete its intercept within the very narrow window that exits for boost-phase intercept. As noted earlier, ICBM boosters typically burn for only 3–5 minutes. Given the time needed to detect the launch of the missile and to calculate the aim point for the interceptor, only 2-4 minutes would typically be available for an SBI to reach a ballistic missile booster. For example, assuming a 60-second commit time, the range of a 6 km/sec SBI would be no more than 500–1,000 km (depending on whether the target was a solid or liquid fuel ICBM).[135]

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132 At high-speeds, colliding with even small particles might well destroy or disable a satellite.

133 Wright et al, *The Physics of Space Security,* p. 137.

134 Ibid.

135 Derived from Figure 2-2, Arthur and Roy, *Alternatives for Long-Range Ground Attack*, p. 9.

By contrast, such extremely prompt intercept speeds are unlikely to be critical in the case of satellite intercept. And if the time available for the SBI to travel to its target is expanded, from 2-4 minutes, to tens of minutes or even hours, its range would increase dramatically. An SBI ASAT would also have a significant capability against satellites located at higher orbits. According to one estimate, an SBI stationed in low-earth orbit could reach geostationary orbit in roughly 5 hours, assuming a speed of 2.4 km/sec. If the speed were increased to 4 km/sec, the time needed to intercept such a satellite would decrease to only about 1.5 hours.[136]

Since SBIs intended for an ASAT—rather than a boost-phase ballistic missile defense—role could be made smaller, the procurement costs might be substantially lower. A reasonable estimate is that the unit procurement costs for an SBI ASAT would be about half as much as for an SBI designed for boost-phase ballistic missile intercept.[137] Moreover, assuming that response times measured in tens-of-minutes to hours, rather than minutes, would be sufficient (allowing for far greater intercept ranges), a much smaller constellation of SBIs would be needed—at least in theory—to constitute a meaningful ASAT capability than would be needed to provide even a minimal boost-phase ballistic missile defense capability. That said, precisely how many SBIs would need to be deployed to constitute a meaningful ASAT capability is far from clear.

Calculating the total number of SBIs that would have to be deployed in orbit to ensure, at least in theory, the ability to intercept one or more ICBMs launched against the United States from North Korea or Iran is not a simple exercise, but it is relatively straightforward—once assumptions are made about booster burn time, commit time and interceptor speed. By comparison, estimating the number of SBIs that might be needed to conduct ASAT missions is far more complex. Moreover, ultimately, the answer is likely to be largely dependent on subjective judgments about a variety of factors concerning, among other things, how many satellites the US military should be capable of intercepting, and how quickly it should be capable of making these intercepts.

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136 Wright et al, *The Physics of Space Security,* p. 137.

137 Assuming SBI procurement costs would be proportional to the mass of the system, the unit procurement cost of an SBI ASAT might be only one-third as much as for an SBI designed for the boost-phase ballistic missile defense mission. However, not all costs will vary with the mass of the system (e.g., for guidance components). Moreover, since the total number of SBIs purchased would likely be far smaller in the case of the ASAT mission (and, thus, economies of scale reduced), average unit procurement costs would probably be somewhat higher than they would otherwise be.

Some idea of the number of satellites the US military might want to be capable of disabling or destroying in wartime may be gained by considering a possible future conflict with China. Such a conflict represents perhaps the most stressful and challenging the United States would face involving a substantial wartime competition in space.[138] China currently has a total of some 36 satellites in orbit. However, only a fraction of these satellites may possess capabilities that could pose a significant threat to the effective operation of US military forces. This suggests that a handful of SBI ASATs could provide the US with a meaningful capability.

On the other hand, this may understate the number of satellites the US military would want to be capable of attacking in a future conflict with China. In 2025, for example, China may have substantially more satellites than it has today. The United States currently has in orbit about 65 military satellites, as well as some 200 civilian satellites used by the US military. It may be unlikely that China will acquire a similarly large inventory of satellites over the next 20 years. However, it is certainly possible that the number of Chinese satellites could grow to as many as one hundred over this period, and that the US military would wish to target all of these.

The above discussion suggests that the number of satellites the US military might wish to target in a future conflict could vary significantly, from as few as a handful (e.g., 10) to perhaps 100. The higher of these two figures would also be consistent with the number of air-launched miniature homing vehicle (ALMV) ASAT interceptors the Defense Department reportedly planned to purchase before that program was cancelled in 1986.[139] This suggests that an ASAT constellation consisting of as few as 10–100 SBI might prove sufficient. On the other hand, depending on the constellation's precise architecture, how quickly it was deemed necessary to have each enemy satellite destroyed, assumptions about potential countermeasures, and other considerations, more than one SBI might need to be deployed for each enemy satellite the US military wished to target.

Assuming that an SBI ASAT would have a substantially lower unit cost than an SBI designed for boost-phase ballistic missile defense and that fewer (and possibly far fewer) SBIs would be needed to constitute a meaningful ASAT capability than for ballistic missile defense, the total procurement cost for such a system would be substantially, and perhaps dramatically, lower. If unit procurement costs were half that of an SBI

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138 O'Hanlon, *Neither Star Wars Nor Sanctuary*, p. 91.
139 See www.globalsecurity.org/space/systems/almv.htm.

designed for boost-phase ballistic missile defense, a constellation of ten to 100 SBI ASATs would have total procurement costs (over the 20-year life of the constellation, and including spare and replacement systems[140]) of some $800 million to $8 billion[141] (see Figure 3).

Developing an SBI ASAT capability would also probably cost less than developing an SBI boost-phase ballistic missile defense capability. Among other things, this is because such a system would not, as noted earlier, need to be as maneuverable. In addition, depending on the response time deemed necessary or desirable, an SBI ASAT could be made with a lower top speed.

A reasonable, though only very rough, estimate of the cost of developing an SBI ASAT would be $4–11 billion. The higher estimate assumes that developing such a system would cost as much as developing the slower and less technologically advanced of the two SBI options included in CBO's 2004 study of boost-phase ballistic missile defense options, and that the program would—consistent with historical trends—experience substantial cost growth.[142] By contrast, the lower estimate assumes that developing such a system would cost only half as much as projected by CBO for its low-cost SBI option, and that the program would experience no cost growth.[143] The above discussion suggests that total acquisition costs for an SBI ASAT constellation consisting of 10-100 interceptors would be about $5 billion to $19 billion. However, as noted earlier, it is possible that a larger constellation of SBIs would need to be deployed to effectively target 10–100 enemy satellites, and this larger constellation would have proportionally higher procurement costs.

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140 Consistent with CBO's estimate of the total number of SBIs that would have to be procured to support an SBI constellation designed for boost-phase ballistic missile defense, it is assumed in this estimate that for every deployed SBI about 2.5 replenishment and spare SBIs would have to be purchased over the system's 20-year operational life.

141 The lower figure is for a 10-SBI constellation and assumes that unit procurement costs would be half that of the low-end estimate projected for the 4 km/sec SBI included in CBO's Option 4. The higher figure is for a 100-SBI constellation and assumes that unit procurement costs would be half that of the high-end estimate included for this system in CBO's Option 4. Arthur and Roy, *Alternatives for Boost-Phase Intercept*, p. 42.

142 Ibid.

143 This approach to estimating R&D costs assumes that those costs would be proportional to the SBI's unit procurement cost (i.e., an SBI with unit procurement cost half that projected for an SBI designed for boost-phase ballistic missile defense, would likewise cost half as much to develop). It has been used by CBO to estimate, among other things, the cost of developing booster rockets of various sizes. Ibid., p. 46.

Satellite hardening would probably not be an effective countermeasure against an SBI armed with a homing interceptor, given the very high speeds at which the kill vehicle and satellite would collide. However, this kill mechanism can also be a liability; a major problem with using SBIs or other kinds of (space- or terrestrial-based) kinetic-energy weapons (e.g., space mines and surface-based interceptors) in the ASAT role, is that successful intercepts would cause space debris. In turn, this debris could itself pose a significant threat to the survivability of US satellites, and those of friendly or neutral countries. Although the Air Force has explored the development of kinetic-energy interceptors designed to reduce the amount of debris created, it is unclear how effective such techniques would be.[144] Concerns about space debris are so great among US military planners that some, such as Gen. Ralph Eberhart, the former head of US Space Command, have suggested that using kinetic-energy ASATs to target enemy satellites might, because of the debris successful intercepts would create, do more harm than good in terms of furthering US security interests.[145] While satellite hardening would probably not work, other kinds of countermeasures (discussed in Chapter 4) might, at least in some cases, prove effective against this type of ASAT capability.

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[144] Theresa Hitchens, Michael Katz-Hyman, Jeffrey Lewis, "US Space Weapons: Big Intentions, Little Focus," *Nonproliferation Review*, Vol. 13, No. 1, March 2006, p. 38.

[145] Kerry Gildea, "Space Command Chief Questions Value of KE-ASAT," *Defense Daily*, March 29, 2001.

Figure 3: Cost Estimates for Illustrative ASAT Systems
(in 2007 dollars)

System	Cost*
Space-Based	
Space-Based Interceptor (SBI)	$5–19 billion
Space Mine	$100 million to $2 billion
Space-Based Laser (SBL)	several billion (or less) to $60 billion**
Space-Based Jammer	NA
High-Powered Microwave (HPM)	$200 million to $5 billion
Terrestrial-Based	
Surface-Based Kinetic-Energy Interceptor	$0–3 billion^
Ground-Based Laser	$4–6 billion
Airborne Laser	$0–6 billion^
Airborne Kinetic-Energy Interceptor	$3 billion
Ground-Based Jammer	tens of millions+
Nuclear Weapon	^^

* Estimates generally include development and procurement costs associated with acquiring the system and (once fully deployed) operating it for 20 years.
** Range reflects difference between SBL constellations designed to dazzle/blind (low estimate) satellites, versus structurally damage/destroy (high estimate) satellites.
^ Represents an estimate of the marginal cost of giving a limited ASAT capability to weapon systems which, under current plans, the US military already has or is in the processes of acquiring for the ballistic missile defense mission (see Figure 1 for an estimate of the full cost of these systems).
^^ Costs would be minimal for a country that already has nuclear weapons. But for countries that do not, acquiring such a weapon could be both very difficult and costly.

Space Mines

Space mines are another space-based weapon that could be used to destroy satellites in orbit through kinetic-energy kill mechanisms. Unlike an SBI ASAT, which would make use of a high-velocity direct ascent interceptor to reach and kill its target, a space mine would be lofted into its own orbit. Space mines could be launched into orbit during a crisis, or perhaps years in advance of a possible future conflict.

These weapons, like SBI kill vehicles, could be designed either to collide directly with the target satellite or to produce a pellet cloud that would destroy the satellite. Such a weapon could be stationed in space in a number of ways.[146] It could be placed in the same orbit as its intended victim, trailing nearby, a fixed distance away, and detonated on command. Or, it could be placed in the same orbit, but much further way. In that case, the space mine would have to be maneuvered to approach and attack the target. Alternatively, a space mine could be placed in a crossing orbit that would, periodically, place it within striking distance of its intended target.

Space mines could be made quite small and lightweight. Using current or near-term technology it would probably be possible to create space mines that fall into the "microsatellite" class (roughly 10 to 100 kilograms). Even smaller space mines could be constructed in the future. The United States and a wide variety of other countries are researching and developing microsatellites, and even smaller satellites (such as one-to-ten kilogram nanosatellites, and picosatellites that weigh under one kilogram), for a wide variety of roles.[147] Small size is a potentially important characteristic for a space mine, since it might make covert deployment possible in some cases.

Most satellites are launched from a small number of sites, with the launches announced in advance. However, it might be possible to conceal launches of small payloads, from some observers, by using aircraft and smaller ground- and sea-based sites.[148] Alternatively, an attempt could be made to deploy a small space mine, unnoticed, from the same launcher used to deploy another, larger commercial or military satellite.[149] Because of its extensive, and unmatched, global network of early warning satellites, optical sensors and space tracking radars, it is unlikely that, at present, such surreptitious deployments would go undetected by the United States.[150] In any case, even if their launch could be successfully concealed, such satellites might well be detected once in orbit, especially if they engaged in any maneuvering.[151]

While it would be difficult, at least in the near term, for any other country to place a space mine into orbit without the United States detecting it, it might be possible for the United States to secretly place such a satellite

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[146] Wright et al, *The Physics of Space Security*, p. 151.
[147] O'Hanlon, *Neither Star Wars Nor Sanctuary,* p. 86.
[148] Wright et al, *The Physics of Space Security*, p. 152.
[149] Ibid., p. 153.
[150] Ibid.
[151] Ibid.

in orbit. And, at least at some point in the future, it may be possible for another country, such as China, that has developed microsatellite technology, to place small space mines in orbit covertly.[152]

The cost of developing and procuring space mines is difficult to estimate. Among other things, this is because the space mines could vary substantially in terms of size and sophistication. Based on historical cost relationships between satellite weight and costs, however, and assuming average system complexity, a reasonable estimate is that space mines in the 10-100 kilogram class would cost an average of some $5–25 million to acquire.[153] Assuming, consistent with the above discussion of SBI ASAT requirements, that the US military would want to be capable of targeting 10-100 enemy satellites, total acquisition costs for such a system would be projected to range from some $100–500 million for 10 space mines, to perhaps $500 million to $2 billion for 100 space mines.[154] Development costs might account for as much as half of total acquisition costs in the case of a 10-satellite purchase, and 15 percent of those costs in the case of a 100-satellite buy.[155]

This represents only a very rough estimate of possible costs. If it were assumed that these space mines would be of relatively complex design (rather than average complexity), their acquisition costs could more than double.[156] Costs could also vary dramatically depending on whether the US military planned to deploy the satellites just prior to a potential conflict, or

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152 O'Hanlon, *Neither Star Wars Nor Sanctuary,* p. 65.

153 These estimates were derived using the National Aeronautical and Space Administration's (NASA's) Advanced Missions Cost Model (www.72.14.209.104/search?q=cache:9kEv8rMphZgJ:cost.jsc.nasa.gov/AMCM.html+advanced+missions+cost+model&hl=en&gl=us&ct=clnk&cd=1) to estimate system development and procurement costs. The estimated unit acquisition costs are based on a total quantity purchase of 50 systems. These cost estimates also seem roughly consistent with the cost of at least one microsatellite development effort by NASA, the Demonstration of Autonomous Rendezvous Technology (DART) program. This effort, which involved the acquisition and launch of a single microsatellite in 2005, reportedly cost about $47 million. Hitchens et al, "US Space Weapons: Big Intentions, Little Focus," p. 38.

154 These total acquisition cost estimates take into account the impact that changing procurement quantities has on unit acquisition costs. See, NASA's Advanced Missions Cost Model.

155 See, NASA's Spacecraft/Vehicle Launch Cost Model, available at http://72.14.209.104/search?q=cache:Xc1ukKhDee4J:cost.jsc.nasa.gov/SVLCM.html+spacecraft/vehicle+launch+cost+model+NASA&hl=en&gl=us&ct=clnk&cd=1.

156 Ibid.

in peacetime so that each potential target satellite would be continuously trailed.[157] In the latter case, a substantial number of replenishment satellites would also need to be acquired, since each space mine might have a service life of only 7–10 years. As such, the 20-year lifecycle costs of a force of space mines could be more than three times greater than suggested in the illustration above.

Satellite hardening could be an effective countermeasure against space mines armed with pellet cloud warheads if they were located far enough away when fired.[158] However, it would be difficult to harden satellites to withstand the destructive effect of such a space mine if its warhead was fired in close proximity to the satellite, or if it was, like an SBI, armed with some type of homing interceptor.[159] On the other hand, as with SBIs and any other ASATs that rely on kinetic-energy kill mechanisms, the successful destruction of a satellite with such a space mine would create some amount of space debris. This might not deter a country with relatively little dependence on commercial or military satellites, such as North Korea or Iran, from acquiring and using this type of ASAT. It might even be perceived to be an advantage. But the space-debris problem may make this type of ASAT a relatively unattractive option for the United States.

As with an SBI ASAT system, and most other types of ASATs, the use of various other countermeasures, such as decoys and replenishment spares, could substantially reduce the effectiveness of space mines—but much would depend on the specific technologies and techniques employed.

SBL ASAT

An SBL designed for the ASAT mission could destroy or disable its target either by causing structural damage (the same means by which SBLs would attempt to destroy ballistic missile boosters), or by overheating the satellite's body or its solar arrays. A potentially significant advantage to

157 Although fewer space mines would need to be procured in the former case, it could be difficult to deploy a large number of space mines during a crisis without overtaxing current launch capabilities. It might also be more difficult to place space mines in orbit covertly in a crisis, when potential adversaries would presumably be more vigilant.

158 Wright et al, *The Physics of Space Security,* p. 138.

159 Ibid.

the use of lasers—whether space- or terrestrial-based—in the ASAT role is that, unlike ASATs that rely on kinetic-energy kill mechanisms, lasers might cause little or no space debris. On the other hand, the laser's more subtle kill mechanism is also, to some degree, a liability. This is because it can make it substantially more difficult to assess the extent to which, or even whether, the targeted satellite has been damaged.[160] In turn, this may mean an attacker would feel compelled to re-attack a satellite that has in fact already been effectively disabled.

Just as with the SBI, a smaller number of less capable SBLs would be needed to provide a meaningful ASAT capability than to provide even a very modest boost-phase ballistic missile defense capability. One reason for this is because, as noted earlier, compared to the boost-phase ballistic missile defense mission, substantially more time would be available for engaging satellites. To cause damage a laser must deposit some minimal amount of energy on its intended target. The amount of energy deposited on the target will depend largely on four factors: the amount of energy generated by the laser, the size of the mirror used to direct the laser beam, the distance from the laser to the target, and the dwell time of the laser.

To be even minimally effective, each SBL in an SBL constellation designed for boost-phase ballistic missile defense might have to be capable of destroying as many as a dozen or so ICBMs within as little as a minute. As a result, laser dwell times would often be limited to 5–10 seconds per booster. By contrast, an SBL targeting a satellite would likely have far more time available. This has important design implications. If, for example, it is assumed that the laser's beam can be kept on the target for up to 100 seconds, rather than 10 seconds, holding all else constant, the laser's power could be reduced 10-fold with no loss in lethality.

Another important reason why the ASAT mission would be easier for SBLs than the boost-phase ballistic missile defense mission is that satellites are generally softer targets than ballistic missile boosters, especially solid boosters. In the case of a liquid fuel booster some 1,000–5,000 kilojoules per square centimeter (KJ/sq cm) of laser energy would

[160] The effectiveness of such an attack would be especially unpredictable and difficult to assess where the laser attempted to disrupt the satellite by overheating its body (rather than by causing structural damage), or if shielding was used. In such cases, an attacker might only be able to determine the status of the satellite by monitoring changes in its downlink communications or stationkeeping maneuvers. Ibid., p. 135.

have to be deposited on the booster skin to cause its destruction. In the case of solid boosters, the amount of energy required increases to perhaps 10,000 KJ/sq cm.[161] By comparison, it is estimated that a laser could effect a quick kill—through structural damage—against unhardened satellites, with a fluence of 1,000 KJ/sq cm, and could disable an unhardened satellite—through overheating of the satellite's body or its solar arrays—with a fluence of as little a 50 KJ/sq cm.[162]

This means that, holding its technical specifications and other performance characteristics constant, an SBL capable of destroying ballistic missile boosters at a particular range would be capable of destroying satellites at a range several (or even many) times greater. Alternatively, an SBL ASAT could be designed with a substantially smaller mirror, laser, or fuel supply, or some combination of all three, and still be effective. Such an SBL also might not need to be capable of destroying as many targets as an SBL designed for boost-phase ballistic missile defense, further reducing its required fuel supply. All of these potential changes could lead to cost savings by cutting the number of SBLs that would otherwise be required, and/or reducing the acquisition costs of the individual SBLs comprising the constellation.

Just how much less expensive an SBL ASAT constellation would be to develop and procure than an SBL constellation designed for boost-phase ballistic missile defense is difficult estimate with much confidence. This is for many of the same reasons discussed above with regard to SBI ASATs. In this case, in addition to uncertainty concerning, among other things, the number of satellites the US military might want to be capable of destroying, there is also, as noted above, considerable uncertainty about how much laser fluence would be required to disable or destroy various satellites.

A reasonable, order-of-magnitude estimate might be that an SBL designed for the ASAT mission would have a mass only one-tenth as great as that of an SBL designed for ballistic missile defense—reflecting the fact that unhardened satellites could typically be killed or disabled with only one-tenth, or less, the amount of laser fluence needed to destroy a solid fuel ICBM booster. Based on historical relationships between satellite mass and acquisition costs, a weight reduction of this magnitude would be

[161] Preston et al, *Space Weapons, Earth Wars,* p. 111.
[162] DSB, *High Energy Laser Weapon Systems Applications,* p. 49.

projected yield unit procurement costs about 22 percent as high as those estimated for an SBL designed for boost-phase ballistic missile defense.[163] This implies unit procurement costs of roughly $350–450 million.[164]

If the goal were to have the capability to target all potential satellites of interest that were within range, within the first few minutes of a decision to attack, a large constellation of SBLs could be required. If it is as large as the 24-satellite constellation for the boost-phase ballistic missile defense mission described in Chapter 1, total (20-year lifecycle) procurement costs could amount to some $30–37 billion.[165]

A very rough estimate of the cost of developing an SBL designed for the ASAT mission might be $5–23 billion. The higher estimate assumes that developing such a system would cost as much as developing an SBL system intended for ballistic missile defense.[166] By contrast, the lower estimate assumes that—consistent with its projected lower unit procurement cost—developing an SBL ASAT would cost only about one-fifth as much as developing the latter type of system. This suggests that total acquisition costs for an SBL ASAT constellation consisting of 24 satellites would be on the order of $35–60 billion.

If a less immediate response time were deemed adequate, or it was assumed that overheating was a reliable means of disabling a typical satellite,[167] it might be possible to make due with a much smaller constellation, and/or substantially less capable SBLs—leading to significant cost savings. On the other hand, a far more capable, and more costly, SBL

163 This estimate was derived using NASA's Spacecraft/Vehicle Level Cost Model, available at http://cost.jsc.nasa.gov/SVLCM.html.

164 The lower figure uses CBO's low-end estimate of unit procurement costs (for an SBL designed for the ballistic missile defense mission) as the baseline from which to estimate the costs of an SBL intended for an ASAT role, while the higher figure uses CBO's high-end estimate of those costs as the baseline from which to generate this estimate. CBO, "Estimated Costs and Technical Characteristics of Selected National Missile Defense Systems," p. 23.

165 Consistent with CBO's 2002 cost estimate for a 24-SBL boost-phase ballistic missile defense system, this estimate assumes that, once the constellation reached its full strength of 24 SBLs, an average of three replenishment satellites would have to be procured each year to maintain the constellation.

166 CBO, "Estimated Cost and Technical Characteristics of Selected National Missile Defense Systems," p. 23.

167 As noted earlier, a potentially serious limitation of relying on this kill mechanism is that it is more difficult to assess the effectiveness of such an attack than it is in the case of (higher-power) laser attacks that cause structural damage.

design might be needed if the goal was to engage satellites stationed not only in low-earth orbit but in higher orbits as well. In addition, as in the case of SBL constellations designed for ballistic missile defense, the use of even relatively simple and modest countermeasures could substantially reduce the effectiveness, or increase the required capabilities (and thus cost) of an SBL constellation intended for the ASAT mission.

As noted in previous chapters, structures can be protected from laser energy to varying degrees through a variety of means. In the case of satellites, exposed surfaces could be hardened, shields could be added (including lightweight "shadow shields" deployed between the satellite and the threatening SBL), and "reactive passive" countermeasures could be taken (e.g., smoke released from the targeted satellite that would interfere with the propagation of the laser beam). Achieving and maintaining a significant ASAT capability against such hardened satellites might require a substantially, or even dramatically, more capable (and thus more costly) constellation of SBLs than assumed above. Like the other ASAT systems discussed in this chapter, an SBL constellation designed for an ASAT role could also be susceptible to a range of other countermeasures—the employment of which could significantly reduce its effectiveness and/or increase its costs.

Dazzling and Blinding

An SBL could also be used to dazzle or blind reconnaissance satellites equipped with optical sensors, rather than to destroy them. Dazzling involves using a laser to temporarily swamp a satellite's optical sensor with light that is brighter than the object the sensor is trying to image.[168] Conceptually, dazzling is comparable to the electronic jamming used to interfere with radar sensors and radio communication links. In the case of a blinding attack, which requires the use of a higher intensity laser beam, the goal is to essentially melt the optical sensor's detector material or electronic connections, causing permanent damage.

Although a higher intensity beam is generally needed in the latter case than in the former, both types of attack may require far less laser energy to effectively execute than is required for laser attacks intended either

[168] This discussion of dazzling and blind draws heavily from Wright et al, *The Physics of Space Security*, pp. 125–130.

to destroy or disable other types of satellites, or to destroy or (through less subtle means) disable satellites equipped with optical sensors. The potential for even relatively low power lasers to effectively interfere with optical sensors carried aboard reconnaissance satellites was pointedly illustrated in 1997 when a ground-based, 30-watt tracking laser with a 1.5 meter diameter mirror was, inadvertently, used to dazzle the sensor of an imaging satellite orbiting at an altitude of 500 km.[169]

Dazzling attacks could be countered by either directing the sensor to look in a different direction or closing the sensor's shutter to block the dazzling laser energy from reaching the sensor. However, adopting either of these options would have essentially the same effect as being dazzled—since neither option would allow the sensor to view the area of interest. On the other hand, depending on the details of the satellite's optical sensor, including its resolution, the degree to which it is designed to control stray light, and whether it makes use of multiple detectors and filters (as well as the extent to which the attacker knows these details), effectively dazzling such a sensor could prove difficult.[170]

In any event, SBLs are unlikely to be used to dazzle imaging satellites. This is because, to be effective, a dazzling laser must remain within the sensor's field of view, which is very narrow for high-resolution imaging satellites.[171] And it would be extremely difficult, if not impossible, to position an SBL in such a way as to maintain it in orbit within this narrow window for an extended period of time.

SBLs could, however, be used to blind imaging satellites. In this case, if the laser was sufficiently bright, it could cause permanent damage to the satellite's sensor even if it was in its field of view for only a short time. According to one estimate, continuous wave "lasers with output powers of tens of watts or pulsed lasers with pulse energies of millijoules—appear to be capable of damaging small sections of a detector, corresponding to ground areas roughly 1 meter in size," while increasing the size of the damaged region by a factor of 10 would require increasing laser power by a factor of 100.[172]

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[169] Ibid., p. 128; and Laura Grego, "A History of Anti-Satellite Programs," Union of Concerned Scientists, p. 6., available at www.ucsusa.org/global _security/space_weapons/a-history-or-asat-programs.html.

[170] Wright et al, *The Physics of Space Security*, pp. 127–28.

[171] Ibid., p. 128.

[172] Ibid., p. 129.

These specifications suggest that an SBL designed to blind optical sensors carried aboard reconnaissance satellites could be substantially smaller and less complex, and thus less costly, than one designed to destroy or disable satellites through other means. Estimating just how much less costly such an SBL might be to develop and deploy would be very difficult. However, given that the power levels required for this mission could be several orders-of-magnitude below the level needed to destroy a ballistic missile booster, or even a satellite body, it may be reasonable to conclude that the cost of acquiring such a capability would be far lower than for these other two missions—e.g., several billions of dollars, or perhaps even substantially less.

Jamming and Spoofing

The effectiveness of all types of satellites could be reduced through jamming or spoofing satellite communications. Satellites transmit important information down to ground stations, including images and other intelligence collected by their sensors. Likewise, ground stations send critical instructions concerning, for example, where to focus their sensors, up to satellites. Signals directed down to ground station are referred to as the *downlink*, while those directed from the ground station up to the satellite are referred to as the *uplink*. Jamming consists of interfering with the signal in order to block or impede communications, while spoofing involves trying to imitate the signal and getting the receiver to accept false information or instructions.

Unlike most other ASAT technologies, the effects on satellites of electronic jamming and spoofing are temporary and reversible. In some circumstances this may be a major advantage. Among other things, during a crisis, temporarily negating a satellite's capabilities without physically damaging or destroying it might be viewed as a less significant step, in terms of conflict escalation. Such a capability could also prove useful if the satellite in question provided important data (e.g., imagery) to an adversary, but was owned and operated by a neutral country. Another important advantage of electronic jamming is that, unlike kinetic-energy ASATs, since they do not physically damage the targeted satellites, they do not create any space debris.

Both terrestrial-based and space-based systems could be used to jam satellite downlinks and uplinks. In both cases, however, terrestrial-based systems are likely to prove more effective. The effectiveness of a jammer or spoofer depends, among other things, on the relative power of the jammer and the satellite signal. Terrestrial-based jammers can generally be deployed far closer to the downlink receiver than space-based jammers. This is a significant advantage since the strength of radio signals, like all electromagnetic emissions, decreases with the square of the range. This limitation would likely make it completely infeasible to use satellites in geosynchronous or semisynchronous orbit as effective downlink jammers.

In theory, satellites in low-earth orbit could make more effective downlink jammers, since they would be 50–100 times closer to the ground stations they would be attempting to jam. However, this too might be impractical. In this case, the problem is the absentee issue discussed earlier. Specifically, since satellites in low-earth orbit are continuously orbiting the earth and the earth is itself rotating, a very large number of jammer satellites would need to be kept in orbit to ensure that one was always within the broadcast/receive area of a particular ground station's receiver.[173]

Using space-based systems to jam uplinks to satellites might make more sense. Since such satellites could be placed in orbits that would take them much closer to the satellites they would be attempting to jam than terrestrial-based systems, such space-based jammers might need far less power than terrestrial-based systems. However, for optimum performance, a jammer satellite would have to be kept in a lower orbit than the satellite it was trying to jam—so that it would be located within the broadcast/receive area of the satellite's antenna. In turn, since satellites in lower orbits travel at higher speeds than higher altitude satellites, the jamming satellite would quickly cross and move out of that area.[174]

In order to get around this problem, the jammer satellite could be placed, some distance away, in the same orbit as the target satellite. But in this case, the jammer would not be positioned within the main broadcast/receive area of the target satellite's antenna. Since the antenna's sensitivity is likely to be "many tens of times less" in this direction than when the signal is coming from in front of the antenna, a jammer satellite so positioned would require far more power to effectively jam the satellite's uplink signal.[175] Indeed, according to at least one source, the disadvantages

173 Ibid., p. 120.
174 Ibid., p. 123.
175 Ibid.

inherent in having to direct the jamming signal through the “side lobes” of the target satellite’s antenna could easily offset the theoretical advantage that proximity would otherwise confer to placing the jammer in space.[176]

Despite the fact that, in general, both downlink and uplink jamming could probably be performed more effectively with terrestrial-based systems than space-based systems, there might be some instances in which such a system would prove useful. The cost of such a system could vary dramatically, depending among other things, on the effective range intended for the system and whether it was designed for jamming or spoofing—with the latter kind of system generally requiring substantially more complex and costly technology.

Because of the complexity of specifying system requirements and performance characteristics for a jammer satellite, or an appropriate system architecture for a constellation of such satellites, no attempt is made in this analysis to make even a rough estimate of the cost of acquiring and supporting such a system. Perhaps the most that can said is that, based on the discussion above, a constellation of space-based jammers is likely to cost more to acquire and operate than a comparably-capable terrestrial-based system. As discussed later in this chapter, the Air Force is acquiring a small number of mobile ground-based jammers, designed to disrupt communications between satellites and their ground stations, for a total program cost of some $75 million.

High-Powered Microwave Weapons

Lasers are not the only directed energy weapons that could, in theory, be used to attack satellites. Another possibility would be high-powered microwave (HPM) weapons. Microwaves are shorter than radio waves, but longer than laser light waves. Radars and communications links often make use of microwaves. Microwave radiation can disrupt a satellite’s electronics and, if sufficiently intense, permanently damage them.

To be effective, the microwave radiation must enter and “couple” to some component.[177] If the microwave enters through the satellite’s antenna and is of a frequency it accepts, even relatively low power levels

[176] Ibid.

[177] The following description of HPM weapons draws heavily from Ibid., pp. 130–33.

might be enough to disrupt or disable the satellite. Successfully carrying out such a "front door" attack, however, requires having relatively detailed technical knowledge of the target satellite's technical specifications. In addition, to be effective, the HPM weapon must be used when it is within the broadcast/receive area of the satellite's antenna.

Rather than attacking through the satellite's antenna, HPM weapons could also be used for "back door" attacks. There are two advantages to this kind of attack. First, the weapon can be used even when it is not within the broadcast/receive area of the satellite's antenna. Second, the HPM weapon need not operate at the same frequency as the target satellite. Against these advantages, however, is one critical disadvantage. Back door attacks—because they are not collected and amplified by the satellite's receiver—require significantly higher power levels to be effective.

Another limitation of HPM attacks of both types is that the effect of such attacks may be difficult to predict with confidence, or assess after an attack. This is especially true in the case of back door attacks, where the ability of the microwaves to enter and couple with a satellite's components may depend on the quality of the satellite's construction, the impact of aging and other, relatively subtle, considerations that may be difficult to measure or anticipate. But a substantial amount of uncertainty may also exist in the case of front door HPM attacks—if there are gaps in the attacker's knowledge of the satellite's design. As one source put it, depending on the details of the satellite's design, a particular HPM attack could be "destructive, disruptive or completely ineffective."[178] It is also possible, at relatively low cost, to harden electronic components against HMP strikes—increasing the amount of energy needed to damage the satellite by "orders of magnitude."[179]

Because the intensity of microwaves, like all electromagnetic radiation, decreases with the square of the distance it travels out from its source, and high-powered microwaves cannot effectively penetrate the earth's atmosphere, an HPM weapon used in an ASAT role would probably have to either be based in space, or lofted into space just prior to use.

Given the relative immaturity of HPM technology, it is difficult to describe what an ASAT relying on this technology would look like, let alone what such a weapon would cost to develop and field. However, according

178 Ibid., p. 133.
179 Ibid.

to one report, a 400 kilogram device, using an explosive generator (and thus having only a "one-shot" capability), could produce a single two-to-five gigawatt HPM pulse.[180] Such a weapon, using a one-meter diameter focusing antenna, might be able to disrupt a computer on an unshielded satellite located 1 kilometer away in the case of a back door attack, and "tens of kilometers" away in the event of a front door attack.[181] Against hardened satellites, these ranges might be dramatically lower.

Given the existence of substantial uncertainty concerning the specific technical characteristics of an HPM designed for the ASAT role, providing even a rough estimate of the potential cost of such a system is especially difficult. However, based on historical cost trends for satellites, adjusted for weight, and assuming average complexity, the unit acquisition costs for a 400-kilogram space-based HPM weapon of this size might be projected to be some $60 million.[182] Given the relatively short-range of such a weapon, even against unhardened satellites, and assuming these weapons would have only a one-shot capability, at least one HPM weapon would have to be procured for every satellite to be targeted. Total acquisition costs could range from some $1 billion to $5 billion, given a target set consisting of 10–100 satellites.[183]

Over a twenty-year period, the number of such weapons that would have to be procured could more than triple, with a commensurate increase in costs, if it was assumed that—rather than being placed in orbit only in the event of a crisis, when the prospect of war seemed relatively close at hand—these weapons would be placed in orbit in peacetime, and a full constellation maintained in orbit at all times.[184]

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[180] Carlo Kopp, "An introduction to the Technical and Operational Aspects of the Electromagnetic Bomb," Australian Air Power Studies Centre Paper 50, November 1996, cited in Wright et al, *The Physics of Space Security*, p. 132.

[181] Ibid.

[182] Estimate was derived using NASA's Advanced Missions Cost Model.

[183] Development costs might account for as much as half of total acquisition costs in the case of a 10-satellite purchase, and 15 percent of those costs in the case of a 100-satellite buy. See, NASA's Spacecraft/Vehicle Launch Cost Model.

[184] This estimate assumes that, once placed in orbit, each HPM ASAT would have an operational service life of 7–10 years.

Terrestrial-Based ASAT Alternatives

As the discussion above makes clear, space-based ASATs, like space-based global strike systems, could be developed and deployed at substantially (and in some cases, dramatically) lower cost than space-based ballistic missile defenses. However, as in the case of the global strike mission, there are a range of terrestrial-based alternatives that could also perform the ASAT mission—should US policymakers decide this is a mission worth pursuing. And these options would generally appear to be less costly, and in some cases dramatically less costly, than the space-based options discussed above.

This is true in part because the cost of developing and deploying these systems is generally lower and partly because, in a number of cases, the US military already possesses or is currently developing terrestrial-based weapons optimized for other missions, especially ballistic missile defense, that have an inherent ASAT capability. In these cases, the relevant cost is not the *total* cost of acquiring and supporting these systems, which have been or will be fielded in any event, but the *marginal* cost of any modifications needed to refine or improve the inherent ASAT capabilities of these weapons. And those costs, at least in a number of important instances, are likely to be extremely low.

The fact that the US military already has or is acquiring a number of terrestrial-based systems that have an inherent ASAT capability also means, by definition, that it possesses a hedge against the prospect that, at some point in the future, it may need to rapidly constitute such a capability.

The various types of terrestrial-based weapon systems that could be used in the ASAT role include:

- Surface-based kinetic-energy interceptors;
- Co-orbital interceptors;
- Airborne kinetic-energy interceptors;
- Surface-based lasers;
- Airborne lasers;

- Surface-based jammers;
- Various systems for attacking satellite ground stations; and
- High altitude nuclear explosions.

These systems differ from each other substantially in terms of capability, complexity and cost. In the remainder of this chapter, each of these systems will be discussed in turn. As in the case of the space-based ASAT systems discussed earlier in this chapter, the effectiveness of these terrestrial-based ASAT systems could, in some instances, be significantly reduced through the use of various countermeasures—and overcoming these countermeasures might require acquiring far more capable (and costly) systems or system architectures than those describe below.

Surface-Based Kinetic-Energy Interceptors

Among the least complex ASAT systems would be surface-based missiles armed with kinetic-energy warheads. The simplest such system would use a missile armed with a warhead that would create a pellet cloud in the path of the oncoming satellite. A more advanced version would use a homing warhead. The United States began to develop a dedicated ground-based kinetic-energy ASAT interceptor in the late 1980s.This program was cancelled by the Clinton Administration in 1993. But technology studies were continued, and in FY 1996 the program was revived by Congress.[185] By 2001, some $400 million had been spent on the program and three prototype interceptors constructed.[186] No additional funding has been provided since then, however, and the three prototypes have been placed in storage. Among other things, the program appears to have been terminated because of reservations about the collateral damage such an interceptor could cause to US satellites (as a result of the space debris it would create). In January 2007, China successfully tested a ground-based

[185] Marcia S. Smith, "US Space Programs: Civilian, Military and Commercial," Congressional Research Service, April 22, 2003, p. 12.

[186] Kinetic-Energy Antisatellite, at www.globalsecurity.org/space/systems/ke_asat.htm.

kinetic-energy interceptor. The interceptor, consisting of a homing vehicle placed atop a medium-range ballistic missile, destroyed an aging Chinese weather satellite in low-earth orbit.[187]

Notwithstanding these development and testing efforts, as far as is known based on publicly available information, no country currently possesses a dedicated force of surface-based ASAT interceptors. However, any country that possesses surface-based exoatmospheric BMD interceptors, or short-, medium- or long-range ballistic missiles has an inherent ASAT capability.

This inherent ASAT capability is greatest in the case of surface-based exoatmospheric ballistic missile defense interceptors. As noted earlier, the United States currently operates a small force of such interceptors, including both ground- and sea-based systems, and this force is projected to be expanded in coming years. The ability of this system to intercept effectively enemy ballistic missile warheads in their midcourse phase is questionable, especially if an adversary was to make use of even relatively simple decoys and other countermeasures. However, this system would likely prove highly capable as an ASAT, since, for reasons mentioned already, satellites would generally be much easier targets to hit and destroy than ballistic missile warheads.

Although not designed to carry out as similar a mission as ballistic missile defense interceptors, ICBMs and shorter-range ballistic missiles also have an inherent ASAT capability. A rule of thumb is that a ballistic missile with a maximum range R on Earth can launch the same payload vertically to an altitude of R/2.[188] Thus, for example, an ICBM with a range of 10,000 km would be able to lift a comparable payload to an altitude of some 5,000 km, while a short-range (300 km) missile such as a Scud would be able to lift warheads to 150 km. Moreover, if smaller warheads would suffice for the ASAT mission, the maximum intercept altitude of these systems would be further increased. Thus, for example, a Scud missile that had the size of its warhead reduced from 1,000 kilograms to 250 kilogram could reach an altitude of some 280 km.[189]

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[187] The Chinese ASAT test seems to have confirmed concerns about the potential for kinetic-energy interceptors to cause serious collateral damage as a result of the space debris they can create. Frank Morring, Jr., "China ASAT Test Called Worst Single Debris Event Ever," *Aviation Week*, available at www.aviationweek.com/aw/generic/story.jsp?id=news/aw021207p2.xml.

[188] Wright et al, *The Physics of Space Security*, p. 77.

[189] Ibid.

Although many countries possess ballistic missiles of various ranges that could, in theory, be modified for ASAT use, only relatively technologically advanced countries might be able to equip those missiles with sophisticated homing capabilities. Other countries, perhaps including states such as North Korea and Iran, would probably have to rely on the use of some type of pellet cloud warhead that would require less accuracy. However, a pellet cloud interceptor system operated by such a country might have only a relatively limited capability. This is because the effectiveness of such a system would depend critically on the attacker's ability to accurately determine the target satellite's orbit, time its attack and control the missile interceptor, as well as the interceptor's ability to lift large masses of pellets into orbit.[190]

On the other hand, for more technologically advanced countries, and the United States in particular, modified space-launch vehicles, ICBMs and shorter-range ballistic missiles could prove highly effective ASAT weapons. In most cases, these missiles would presumably be equipped with highly accurate homing warheads, similar, or identical, to those deployed on its force of surface-based kinetic-energy ballistic missile defense interceptors. However, it would also be capable of equipping these missiles with relatively accurate pellet cloud warheads.[191]

Since the United States already possess, and is expanding, its ballistic missile defense capabilities comprised of surface-based kinetic-energy interceptors, and such weapons are even more ideally suited for ASAT attack, it may be less likely that it would make use of space launch vehicles, ICBMs and other ballistic missiles for this mission, but the US military would certainly be capable of doing so. Moreover, the United States long ago demonstrated its ability to use ICBMs to intercept objects in space—specifically, in 1984, in the "homing overlay experiment," the Army used a homing warhead launched from Minuteman ICBM to intercept a Minuteman reentry vehicle (RV). In addition, under current plans, the US military may retain a substantial number of surplus ICBMs over the next decade or two, as a result of its retirement of the Peacekeeper ICBM and the proposed retirement of 50 Minuteman ICBMs. The cost of retaining these missiles and modifying them for an ASAT role would be far less than the cost of acquiring new missiles for this mission.

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190 Ibid., p. 164.
191 Ibid., p. 165.

The United States has spent many billions of dollars developing and fielding its existing surface-based BMD systems. However, the marginal additional cost of exploiting the ASAT capability inherent in these ballistic missile defense systems would be very low. Those costs could approach zero if it is assumed that adding the ASAT mission would not require purchasing any additional interceptor missiles. On the other hand, it might be more reasonable to assume that additional interceptor missiles would need to be purchased to ensure that carrying out the ASAT mission would not so deplete the interceptor inventory as to render the system incapable of effectively performing its primary—ballistic missile defense—mission.

In that case, the marginal cost of adding an ASAT capability to such a system would equate to the marginal cost of procuring additional interceptor missiles. The unit procurement cost of a ground-based interceptor, for example, is currently about $30 million.[192] Thus, by this measure, the marginal cost of adding an ASAT capability to the existing limited US ballistic missile defense system would be on the order of $300 million to $3 billion—assuming, as in the above examples, that the goal were to be capable of destroying as few as ten to as many as 100 satellites.

This might understate the costs to some extent, since there could be some additional costs associated with effectively, or at least fully, exploiting the ASAT capabilities inherent in such a system. On the other hand, it could overstate those costs, among other things, because an interceptor designed for an ASAT role might not need to be capable of the same rapid acceleration and high speed as one designed for intercepting incoming ballistic missile warheads.

One potentially serious limitation of surface-based kinetic-energy ASATs is that, as with their space-based counterparts, a successful intercept would create space debris. As noted earlier, concerns that such debris would harm US and other friendly satellites traveling in similar orbits appears to have led the US military to deemphasize the pursuit of kinetic-energy ASAT capabilities. The fact that China recently tested this kind of ASAT capability suggests that it is less concerned about the debris problem. This may well reflect the much smaller size of China's own constellations of military and commercial satellites. On the other hand, assuming China continues to increase the number satellites it has

[192] This includes the cost of the interceptor's exoatmospheric kill vehicle (EKV) and booster. See, Ground-Based Interceptor (GBI), at www.missilethreat.com/missiledefensesystems/id.23.css, and DoD, "National Missile Defense Interceptor Booster Selected," Press Release, July 27, 1998.

deployed in space, and the sophistication and cost of those satellites, over time it too may come to see surface-based (as well as space-based) kinetic-energy ASAT capabilities as problematic.

Another limitation of these weapons is that they could only be used to intercept satellites when their orbits brought them within range of the interceptor's launch sites. For example, a satellite traveling in a polar orbit at an altitude of 500 km would come within range of a ground-based interceptor with a maximum range of 1,300 km, only once every 12 hours. It is unclear, whether or how often such a delay would prove especially troublesome, but there might be instances when it would. In any case, since such a US ASAT system (layered upon existing and planned US ballistic missile defense capabilities) would encompass a number of ground- and (mobile) sea-based interceptors deployed in different locations around the world, this limitation could be mitigated to a large extent.

Co-orbital Interceptor

Rather than using a surface-based kinetic-energy interceptor that would travel directly to its target (i.e., a direct ascent weapon), another option would be to launch a "killer satellite" interceptor into orbit that would, within one or several orbits around the earth, intercept an adversary's satellite. Such a system would operate in essentially the same way as the space mines discussed earlier in this chapter. The difference is mainly a function of how far in advance the weapons would be launched into space. While space mines could be placed into orbit years before they were needed and might, in peacetime, continuously (and, if possible, surreptitiously) stalk an adversary's satellite, in the case of a co-orbital system like that developed by the former Soviet Union, the killer satellites would be launched only after a decision had been made to attack a particular satellite, with the intercept (if successful) occurring relatively soon thereafter.

A co-orbital ASAT system was developed by Soviet Union beginning in the late 1960s and tested, intermittently, from the late 1960s through the early 1980s.[193] The system became operational in 1979. Although the system's current status is unclear, it appears likely that it is no longer

[193] For a discussion of Soviet ASAT programs, see Paul B. Stares, *The Militarization of Space: US Policy, 1945-84* (Ithaca, NY: Cornell University Press, 1985), pp. 135–56.

operational.[194] The United States could also develop and deploy a co-orbital ASAT system. Given the similarity of the weapons and technology, such a system would presumably cost roughly the same to acquire and support as an arsenal of space mines. To date, however, the US military has shown little interest in developing a co-orbital ASAT system, viewing such a system as generally more primitive and less effective than ground-based jammers, airborne kinetic-energy interceptors and other ASAT capabilities.

Airborne Kinetic-Energy Interceptor

Another terrestrial-based ASAT option would be to develop and field a kinetic-energy interceptor that could be launched from an aircraft. Such a system would have several advantages over a surface-based interceptor. One advantage is that a missile launched from an aircraft flying at high altitude could be made smaller since it would not need to travel as far. Another advantage is that since an aircraft can be flown into friendly or neutral airspace (e.g., over international waters), it could be deployed relatively rapidly to a position from which it could target any low-earth orbit satellite.

In the mid 1970s, the United States initiated the development of an aircraft-launched kinetic-energy interceptor. The system, known as the air-launched miniature vehicle (ALMV), consisted of a small two-stage rocket armed with a heat-seeking homing vehicle. Like the surface-launched kinetic-energy ASAT discussed above, the ALMV was designed to ascend directly to the targeted satellite. Destruction, in the case of the ALMV, was to be achieved through high-speed collision with the target.

The ALMV was tested several times in the 1980s—twice in 1984 an ALMV was launched from an F-15 fighter against a point in space, and in a 1985 test, the system successfully intercepted an aging US satellite in a 555 kilometer orbit.[195] Plans, at the time, called for conducting a total of 12 flight tests of the system. However, at the end of 1985 the Democratic-controlled House and Republican-controlled Senate included a ban on further ASAT testing in the FY 1986 defense authorization act.[196] Subsequently, the Air Force dropped its efforts to continue development of the ALMV.

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194 Center for Nonproliferation Studies, "Russia: Military Programs, Anti-Satellite (ASAT) Weapons," at http://cns.miis.edu/research/space/Russia/mil.htm.

195 Grego, "A History of Anti-Satellite Programs," p. 4.

196 Ibid.

In 1986, total costs for the program were projected to be about \$5.6 billion.[197] Reportedly, the plan called for buying a total of some 100 interceptors.[198] Congress had provided the ALMV program with about \$2.5 billion prior to its cancellation. This suggests that the Air Force might be able to revive and complete this program for as little as some \$3 billion. In recent years, however, DoD and the Air Force have expressed little interest in doing so. It is also possible that, even now, the Air Force retains some minimal capabilities from this truncated program.

Ground-Based Laser

Ground-based lasers could also be used to attack satellites. A 2001 DSB panel suggested that a ground-based COIL laser with a power output of "several" megawatts and a 3-meter mirror could make an effective ASAT weapon.[199] According to the DSB report, such a system would be capable of destroying satellites in low-earth orbit with altitudes of up to 1,000 km and typical ranges on the order of 2,000 km, and would have a "minimal" capability against satellites in geosynchronous orbit and intermediate altitudes.[200]

The DSB estimated that constructing a single GBL site would cost about \$2 billion.[201] With the rates of cost growth typical of such high-tech weapons systems, a better estimate might be \$2.5–3 billion. A GBL could, in theory, disable or destroy a satellite within its range in a matter of seconds or tens of seconds. However, as with ground-based kinetic-energy interceptors, a ground-based laser would, of course, be capable of attacking satellites only if and when their orbits brought them within range of the laser. And this might happen no more frequently than in the case of a surface-based kinetic-energy interceptor site.[202] As in case of particular surface-based kinetic-energy interceptor sites, there is also a possibility that satellites in certain orbits would never pass within range of the GBL site.

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[197] DoD, "Selected Acquisition Report, September 1986," at http://www.acq.osd.mil/ara/am/sar/1986-SEP-SARSUMTAB.pdf.

[198] Air-Launched Miniature Vehicle (ALMV), at www.globalsecurity.org/space/systems/almv.htm.

[199] DSB, *High Energy Laser Weapon Systems Applications*, p. 49.

[200] Ibid., p. 49.

[201] Ibid., p. 53.

[202] This would depend on the range of the respective systems.

A potentially serious limitation of the GBL, from which surface-based kinetic energy interceptors do not suffer, is that it would not be capable of targeting any satellites that passed within range during periods of cloud cover. The problem posed by cloud cover could be mitigated—though not eliminated entirely—by constructing two or three sites at widely separated locations. Constructing multiple GBL sites would also reduce the amount of time that would generally pass before a particular satellite would pass within range of such a site—in the same way that, as discussed above, operating multiple ground- and sea-based kinetic-energy interceptor sites would improve the response time of such a system.

But increasing the number of GBL sites would substantially increase the cost of such a system. For example, even assuming that R&D activities would account for half of the cost of constructing a single GBL site, and that no additional development costs would be incurred in building the second two sites, acquiring a GBL capability consisting of three sites would be projected to cost some $5–6 billion.

Airborne Laser

Although designed for the ballistic missile defense role, the ABL, discussed earlier, could also have a significant ASAT capability. As in the case of surface-based BMD kinetic-energy interceptors, this capability is inherent in the system. Indeed, the ABL, like surface-based interceptors, could well prove more capable in the ASAT role than as a ballistic missile defense weapon. As noted earlier, the ABL is expected to have a maximum useful range of about 600 km against liquid fuel ICBM boosters, with that range falling to 300 km in the case of solid fuel ICBM boosters. It would presumably have a far greater range if used to target satellites. This is largely for the same reasons discussed earlier in the case of the SBL: satellites are generally softer targets than ballistic missile boosters, are easier to detect and track, and can be dwelled on by the laser for much longer periods of time.

These considerations suggest that even if the ABL's ability to target ICBM boosters is relatively modest, it could have a significant ASAT capability. The main difficulty with converting the ABL to into an ASAT would probably concern its present lack of a capability to detect and track satellites.[203] For the ballistic missile defense mission, the ABL relies on the missile's hot booster plume for detection and tracking. Since satellites provide no such signature, an alternative means would have to be found for accomplishing these tasks. The simplest option would be to use the US military's space tracking and surveillance system to direct the ABL to satellite targets. Providing an effective data link to allow this cuing would require making some modest software and perhaps other changes to the ABL.[204] But those changes could probably be accomplished relatively quickly and at minimal cost.

As noted earlier, developing and procuring a force of seven ABLs is projected to cost some $15 billion. However, as in the case of surface-based ballistic missile defense interceptors, space launch vehicles, ICBMs and other ballistic missiles, the relevant cost in this instance is not the total cost of the ABL—which is already being developed and, under current plans, will be procured and fielded over the next decade—but the marginal cost of giving this boost-phase ballistic missile defense system an ASAT capability.

Given the fact that satellites would generally be substantially easier to target and destroy than ballistic missile defense boosters, it seems likely that these costs would be quite modest. On the other hand, it might be assumed that some number of additional ABLs would have to be procured and deployed so that the assignment of the ASAT mission to the ABL would not interfere with the system's ability to carry out its primary mission of boost-phase ballistic missile defense. The unit procurement cost of the ABL is projected to be some $1.5 billion. Assuming that 1–4 additional ABLs would be procured to ensure sufficient capacity to carry out both the ballistic missile defense and ASAT missions,[205] the marginal cost of providing the latter capability would be some $1.5–6 billion. In addition, operating costs could substantially increase the cost of this option over the system's lifetime.

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[203] O'Hanlon, *Neither Star Wars Nor Sanctuary*, p. 75.

[204] Ibid.

[205] Among other things, a force of four aircraft might be sufficient to keep one aircraft airborne at all times, or at least to maintain such a round-the-clock capability for an extended period of time.

Terrestrial-Based Jammers

Both space- and terrestrial-based systems could be used to jam or spoof satellite uplinks or downlinks. For reasons discussed earlier in this chapter, terrestrial-based jammers would, in general, probably be more effective in this role than space-based systems. According to publicly available information, terrestrial-based jammers represent the one dedicated (vice inherent) ASAT capability that the US military currently possesses. These capabilities include the Counter Satellite Communications (CounterCom) system, a mobile ground-based jammer designed to disrupt communications between satellites and their ground stations.

This system was declared operational in 2004, when the first unit was delivered to the 76th Space Control Squadron in Colorado Springs, Colorado. Plans call for acquiring at least two more of these jammers.[206] Although the technical details of the CounterCom system are classified, according to Air Force officials, it is similar to other ground-based jammers and is based largely on commercially-available components. The total cost of the program is reportedly about $75 million, including about $22 million for system development.[207] This implies unit procurement costs of perhaps $17 million. If this estimate is correct, it suggests that that the US military could dramatically increase its terrestrial-based satellite jamming capabilities, with an increase in funding that—compared to the costs associated with many other ASAT systems (both space- and terrestrial-based)—would be quite modest, perhaps measured in the hundreds of millions of dollars, or less, rather than billions of dollars.

Attacking Satellite Ground Stations

Another means of disrupting satellite capabilities would be to attack the ground stations that control, monitor and support those satellites, rather than the satellites themselves. Such facilities could be attacked with a wide variety of different capabilities, including long-range bombers or other aircraft equipped with PGMs, cruise missiles and special operations forces (SOF), as well as by hackers targeting the station's computer

[206] Hitchens et al, "US Space Weapons: Big Intentions, Little Focus," p. 38.
[207] Jeremy Singer, "US Declares Satellite Jammer Ready," *Space News*, October 18, 2004, at www.space.com/spacenews/archive04/jammerarch_101204.html. These figures are expressed in current dollars.

capabilities. Given the US military's current dominance in precision-strike capabilities, and the global reach of its air forces, in particular, this may be an attractive ASAT option for the United States. On the other hand, as with many other ASAT options, it is unclear how effective such attacks would be. With proper planning, it may be possible to restore links to satellites relatively quickly, for example, by transferring control to backup stations.[208] Moreover, damaged ground stations would be much easier to repair than satellites.

Since the US military already possesses large and highly capable forces that could be used to attack satellite ground stations and, in any event, needs those forces to carry out a broad range of other wartime missions, no attempt is made in this analysis to estimate the cost of acquiring and supporting those capabilities. However, given the fact that these facilities would presumably differ little, if at all, from many other facilities the US military plans and prepares to attack in wartime, and may be relatively limited in number, the marginal cost of acquiring and supporting the capability to attack satellite ground stations would presumably quite modest.

Nuclear Weapons

Nuclear weapons could be used as effective ASAT weapons. Nuclear weapons could damage or destroy satellites through one of several different mechanisms. If the detonation occurs in proximity to the satellite, it could be destroyed by the blast or radiation (especially x-rays) created by the explosion. Depending on the size of the nuclear explosion and, most importantly, the hardness of the satellite, such a weapon could destroy satellites located as far as several hundred kilometers from the point of detonation.[209]

Alternatively, if a nuclear weapon was detonated at an altitude of one hundred to several hundred kilometers, it would create an intense electromagnetic pulse (EMP) that would likely destroy all unhardened satellites in low earth orbit within line of sight of the explosion.[210] A single such an explosion could kill between 5 and 10 percent of a constellation

[208] Wright et al, *The Physics of Space Security,* pp. 133–34.
[209] O'Hanlon, *Neither Star Wars Nor Sanctuary,* p. 68.
[210] Wright et al, *The Physics of Space Security*, p. 138.

of satellites in low earth orbit.[211] Either one of these mechanisms could damage satellites located thousands of miles away, including (in the case of a one-megaton blast) even unhardened civilian satellites located in geosynchronous orbit.[212]

A nuclear detonation at an altitude of one hundred to three hundred kilometers would also generate a persistent radiation environment that could damage unhardened satellites over a period of days or months.[213] In such an environment, typical satellite lifetimes might be reduced from 5–15 years to only a few months. The impact would be less significant if the explosion were under 50 kilotons, but even a smaller nuclear weapon would have some deleterious effects of this type.[214]

Although nuclear weapons could be used to arm space mines, the simplest and—at least in the case of an EMP attack against satellites in low earth orbit—perhaps most effective means would be launch it into space atop a ballistic missile. In addition, the Outer Space Treaty prohibits the deployment of nuclear weapons in space. More importantly, a country with only a small nuclear arsenal might be reluctant to place one of its warheads in orbit for possible future use.[215]

Nuclear weapons possess a number of potentially significant advantages for use in the ASAT role. These include, among other things:

> ... their economy (relative to other weapons of comparable ranges), their concealabilty (from present surveillance systems), their great lethal range (as compared to kinetic-energy weapons) against unhardened satellites, the difficulty of hardening satellites against nuclear detonations at close range, and their adaptability for delivery by a variety of launch vehicles and orbital platforms, including those with poor guidance accuracy and no pointing capability.[216]

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211 O'Hanlon, *Neither Star Wars Nor Sanctuary*, p. 68.
212 Ibid., pp. 67–68.
213 Ibid., p. 68–69.
214 Ibid., p. 69.
215 Wright et al, *The Physics of Space Security*, p. 138.
216 OTA, *Anti-Satellite Weapons, Countermeasures, and Arms Control* (Princeton, NJ: Princeton University Press, 1986), p. 63.

Against these potential advantages are a number of potentially serious limitations and disadvantages. One limitation is that satellites can be hardened to withstand the radiation and EMP caused by a nuclear detonation occurring at some distance. Moreover, such shielding adds relatively little, perhaps 2-10 percent, to the total cost of the satellite.[217] No amount of shielding can protect a satellite from a nuclear detonation nearby. But by forcing an attacker to expend a single nuclear weapon for each satellite destroyed, shielding can make the use of nuclear weapons in the ASAT role appear to be a much less cost-effective approach—especially for a country that possessed only a small number of nuclear weapons.

Another potential disadvantage of using nuclear weapons as ASATs is that, although a nuclear detonation in space would not (at least directly) cause any casualties or physical damage on Earth, it might nevertheless result in a dangerous escalation of a conflict—possibly even leading to the use of nuclear weapons against terrestrial targets. In any case, for the United States, or any other country that had a substantial investment in satellites in low earth orbit, an ASAT attack with nuclear weapons would almost certainly prove, at best, counterproductive—given the enormous damage that would be caused to unhardened commercial satellites, including many such satellites used by the US military. As discussed above, the United States also possess, or is acquiring, a variety of other weapon systems with inherent ASAT capabilities that are likely to prove effective and could be used in a far more discriminating manner.

On the other hand, for a country that has little invested in satellite capabilities and possess a small number of nuclear weapons, but—compared to the United States and other developed countries—only relatively primitive space access and control technologies, using nuclear ASAT weapons may prove to be a tempting option. This could be especially true if the leadership of the country believed the US military posed a threat to the regime's survival.

The cost of acquiring a nuclear ASAT capability would be driven primarily by the cost of acquiring a nuclear weapon. For the United States or Russia, which already possess thousands of nuclear weapons, the costs would be extremely modest, amounting to little more than the cost of the booster needed to launch the weapon into space. By contrast, for a country that does not currently possess nuclear weapons, the costs and technical difficulties could prove prohibitive. An analysis of the cost

[217] O'Hanlon, *Neither Star Wars Nor Sanctuary*, pp. 69 and 126.

and technical requirements associated with developing a nuclear weapons capability are far beyond the scope of this report. Suffice it to note that, at least for a developing country, nuclear weapons programs are likely, even under relatively favorable circumstances, to require many years and hundreds of million or billions of dollars to complete.[218] On the other hand, although unlikely, it is possible that a country could acquire a nuclear weapon through theft or the black market much more quickly and at much lower cost.

Chapter Summary and Conclusions

As noted at the outset of this report and this chapter, it is impossible to generate more than very rough estimates of the potential cost of acquiring and deploying various space-based ASAT systems—and the estimates provided in this chapter should be treated as even more tentative and preliminary than those included in the Chapters 1 and 2. Nevertheless, it seems clear from the above analysis that, as with space-based prompt-strike capabilities, a space-based ASAT capability could be acquired for far less than a space-based ballistic missile defense system of even very limited effectiveness. Again as in the case of space-based strike systems, however, it is also clear that there are terrestrial-based alternative systems that could provide comparable ASAT capabilities and, in most cases, provide these capabilities at lower cost.

Although generally more expensive than terrestrial-based systems, the cost of space-based ASAT capabilities could vary substantially, depending, among other things, on the specific architecture and capabilities of the space-based system and the number of satellites to be targeted. SBI and SBL systems intended for an ASAT role would not generally need to be as capable as SBI and SBL systems designed for the boost-phase ballistic missile defense mission, or require constellations as large. Thus, costs could be kept lower. However, the costs could still be quite high, perhaps in the tens of billions of dollars. At the other extreme, the acquisition of simple space mines might be relatively inexpensive.

[218] Cost estimates for South Africa's nuclear weapons program, for example, range from about $500 million to $5 billion (current dollars). That program was carried out over some two decades and resulted in the production of seven nuclear weapons before it was terminated in the late 1980s. Lt. Col. Roy E. Horton, III, "Out of (South) Africa: Pretoria's Nuclear Weapons Experience," USAF Institute for National Security Studies, Occasional Paper #27, August 1999.

Terrestrial-based ASAT systems would generally be less costly to acquire, especially in terms of marginal costs. In the case of the United States this is especially true, because the US military already possesses or is developing a wide range of terrestrial-based systems that have substantial inherent ASAT capabilities. These include surface-based midcourse ballistic missile defenses, ICBMs and other ballistic missiles, and the ABL. Modifying these systems for the ASAT mission would be relatively simple and inexpensive.

The United States, Russia and China have each developed and tested dedicated ASAT systems. But only Russia appears to currently possess a dedicated ASAT interceptor capability—a relatively primitive co-orbital system—and it is unclear whether this system is still active. However, many other countries posses a limited inherent ASAT capability, primarily in the form of short- and medium-range ballistic missiles that could be modified for ASAT use. If the country also has nuclear weapons its inherent ASAT capability would be significantly greater.

As with ballistic missile defenses and prompt-strike systems, the effectiveness and cost-effectiveness of ASAT weapons—whether space- or terrestrial-based—could be substantially, and perhaps dramatically, reduced through the use of various countermeasures. Possible ASAT countermeasures include satellite hardening and the use of decoys. On the other hand, some types of satellites might be difficult to protect.

Taken together, these findings suggest that, even assuming the United States would benefit from the acquisition of a significant ASAT capability, there may be no need, at least for the foreseeable future, for the US military to develop and deploy space-based ASAT systems.

Moreover, relying on its existing force of dedicated ground-based jammers and the inherent ASAT capabilities the US military currently possess, or is developing, in a variety of different terrestrial-based systems (rather than developing, testing and deploying dedicated space-based ASAT systems) might help minimize the visibility and provocativeness of the US military's ASAT capabilities. In turn, this could help prevent, or at least defer, an ASAT arms race that it would be very much in the interest of the United States to avoid—because of the unmatched size, effectiveness and cost of its network of satellites, and its greater dependence on those capabilities relative to potential adversaries.

On the other hand, as with space-based prompt-strike capabilities—and in contrast to case with space-based ballistic missile defense systems—it is more difficult to dismiss space-based ASATs on simple affordability and cost-effectiveness grounds. Space-based ASATs may be unnecessary and, in most cases, more costly than comparably-capable terrestrial-based systems, but they are not clearly unaffordable, and in some cases, such as simple space-based mines, could have relatively modest costs.

Chapter 4: Using Space-Based Weapons to Protect US Satellite Capabilities

The previous chapter concerned cost and effectiveness issues related to using space-based weapons in an ASAT role. Another possible mission for space-based weapons would be to protect US satellites. In this case, US space-based weapons would be used to destroy or disable various enemy ASAT capabilities. Such defensive or "bodyguard" satellites could be placed in orbit near the particular satellites they were intended to protect. Alternatively, these space-based weapons could be positioned in orbits from which they might be able to defend a number of satellites, or sectors of space.

Most, if not all, of the different types of space-based ASATs discussed in the previous chapter could, in theory, be used as bodyguard satellites. SBIs, SBLs, and space mines could, for example, all be used to destroy or disable various types of ASATs directed against US satellites under certain circumstances. On the other hand, there are some types of ASAT threats for which bodyguard satellites could provide little or no protection. And these include several ASAT capabilities that would be among the simplest for a potential adversary to develop and deploy over the next 20 years, as well as the most dangerous.

Moreover, even against those ASAT threats for which bodyguard satellites may be better suited, it is far from clear that, at present, investments in such capabilities are necessary, or even warranted. Other countermeasures, including shielding and hardening techniques discussed in the previous chapter, as well as additional ones discussed later in this chapter, may provide more cost-effective and robust means of protecting existing satellite capabilities.

In most cases, bodyguard satellites would also, in practice, be essentially indistinguishable from ASATs. Space-based weapons capable of disabling or destroying enemy ASATs would, by definition, generally be equally or more capable of attacking enemy satellites. As such the development, testing and deployment of bodyguard satellites would represent an escalation of the competition in space—perhaps little, or no less, than would the US acquisition of dedicated space-based ASAT capabilities.

Organization of Chapter

In terms of both content and organization, this chapter differs from the previous chapters of this report. First, since, technologically, bodyguard satellites would closely resemble and, in many cases, be identical to) the space-based systems discussed in Chapters 2 and, especially, Chapter 3, the specifics of those technologies are not discussed in detail in this chapter. Second, and largely for the same reason, this chapter does not include a major discussion of the cost of acquiring and supporting such systems. The estimates provided in the previous chapters, and especially Chapter 3, provide some rough indication of how much such systems might cost and—given the lack unclassified sources describing what the architecture of a constellation of bodyguard satellites would look like—it is difficult to provide any more precise or reliable estimates of potential costs.

Third, although—as with the previous chapters of this report—this chapter first discusses space-based options and then alternative options for accomplishing the same mission, in this case the focus of the latter discussion is on a range of passive countermeasures that might be used to protect US (or other) satellites, rather than terrestrial-based alternative means of matching the capability of bodyguard satellites to destroy enemy ASATs.[219]

Fourth, in contrast to the previous chapters of this report, no attempt is made in this chapter to provide even rough, order-of-magnitude estimates of the cost of developing or deploying most of these countermeasures. In part, this limitation reflects the fact that the interplay between ASAT technologies and techniques, on the one hand, and bodyguard satellites

[219] There are circumstances in which terrestrial-based systems, such as ground-based kinetic energy interceptors or ground-based lasers, for example, could be used to attack space-based ASATs. However, discussions of alternative means of protecting satellites tend to focus on the use of passive countermeasures.

and passive countermeasures, on the other, is highly complex and difficult to model. Equally important, it reflects the fact that passive countermeasures, in particular, are highly classified, both in terms of their potential effectiveness and cost. Nor has CBO or RAND, for example, conducted cost or cost-effectiveness analyses of these capabilities which could be used as a baseline from which to generate cost estimates for such passive countermeasures. It is hoped that this chapter will, nevertheless, provide some useful, albeit general and limited, insights concerning the cost-effectiveness of bodyguard satellites.

Bodyguard Satellites and Emerging ASAT Threats

SBI, SBL and space mines could all be used as bodyguard satellites. Under some circumstances, SBIs and SBLs could be used to destroy or disable space mines, microwave weapons, or surface based kinetic-energy ASATs launched against US satellites. SBIs and SBLs could also be used to attack an adversary's own SBLs and SBIs. Likewise, US space mines deployed within lethal range of an adversary's space-based ASATs could be used as bodyguard satellites. However, bodyguard satellites might provide little or no protection against some of the most serious, and likely, ASAT threats.

Bodyguard satellites would generally be ineffective against single-shot space mines armed with nuclear, kinetic-energy (e.g., conventional explosive) or microwave weapons that had already approached within lethal range. "Such weapons would damage their targets almost instantaneously, if at all, and destroy themselves in the process, leaving nothing of value to shoot back at."[220] The only way around this limitation would be to use the bodyguard satellites preemptively—i.e., use them essentially as ASATs. Moreover, if the enemy space mines were "salvage-fused," so that they would be fired or detonated the moment they came under attack, even preemption would be ineffective.

Another problem is that even if a space mine could be successfully intercepted by a bodyguard satellite, its destruction could create space debris that might itself destroy or damage the very satellite the bodyguard satellite was attempting to protect (or other nearby satellites). If targeted with a space-based kinetic-energy weapon, the destruction of enemy

[220] OTA, *Anti-Satellite Weapons, Countermeasures, and Arms Control*, p. 84.

SBIs, SBLs or other ASATs could likewise create space debris that could, in turn, threaten US and other nation's satellites. As discussed in Chapter 3, concerns about space debris are so great among US military planners that some, such as Gen. Ralph Eberhart, the former head of US Space Command, have suggested that using kinetic-energy weapons to target enemy satellites might, because of the debris successful intercepts would create, be more harmful than helpful to US interests in space.[221]

Bodyguard satellites would also likely be ineffective against nuclear-armed ASATs lofted into space by short- or medium-range ballistic missiles. As discussed in the previous chapter, this would also be among the potentially most lethal forms of ASAT attack. [222]

The above discussion notwithstanding, there may be some situations in which bodyguard satellites could prove effective, and cost-effective. Although opinions differ on the question, an SBI or SBL might, for example, in some cases be capable of intercepting conventionally-armed missile boosters used for direct accent ASAT attacks.[223] Similarly, while a bodyguard satellite would likely be ineffective against a space mine that was orbiting within lethal range of its intended target at the outset of a conflict, such a weapon might be effective if used against space mines that had not yet come this close. Even defending against this kind of threat might be difficult if, for example, the ASAT was a space mine in a crossing orbit, since it could approach at high speeds and from many different directions.[224] On the other hand, the task of the bodyguard satellite could be relatively straightforward if the ASAT was a co-orbital space mine that was only slowly approaching its intended target—though even in this case, concerns about space debris would remain.[225]

A full discussion of the role bodyguard satellites might play in protecting the satellites of the United States and friendly nations, and their cost-effectiveness compared to other means of accomplishing this task, is beyond the scope of this report. At a minimum, however, the above

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221 Gildea, "Space Command Chief Questions Value of KE-ASAT."

222 Developing and deploying such an ASAT system would be relatively simple assuming the country already possessed nuclear weapons. However, as noted in the preceding chapter, acquiring nuclear weapons in the first place could be very difficult and costly.

223 For a discussion of some of the difficulties of using bodyguard satellites for this task, see DeBlois et al, "Space Weapons: Crossing the US Rubicon," pp. 60–61.

224 Wright et al, *The Physics of Space Security,* p. 138.

225 Ibid.

discussion suggests that such defensive satellites would probably provide little or no protection against some of the most serious and likely ASAT challenges. In terms of the cost of acquiring and supporting a constellation of bodyguard satellites, about all that can be said, in the absence of a much more rigorous and comprehensive analysis, is that—as in the case of the space-based ASAT capabilities they closely resemble—costs could be relatively low for some technologies (e.g., space mines), and very high for other technologies (e.g., SBLs). The next section of this chapter considers various passive countermeasures that could be (and, in some cases, have been) used to protect US satellite capabilities.

Passive Countermeasures

Rather than attempting to protect US and other satellites by destroying enemy ASAT capabilities, through the use of bodyguard satellites or other means, a wide range of passive countermeasures could be employed. Some of these countermeasures are truly "passive," such as satellite hardening, while others require some activity by the satellite (such as maneuvering), but are passive in the sense that their effectiveness does not turn on an ability to destroy the threatening ASAT system. As noted earlier, no attempt is made in this chapter to estimate the cost of developing and applying most of these countermeasures—among other things because of the highly classified nature of these programs and activities, and the lack of even very rough open-source estimates of their potential costs and cost-effectiveness.

While this may limit the usefulness of this discussion, it is nevertheless important to understand, at least conceptually, the range of passive countermeasures that are available. Although a number of these countermeasures were mentioned in the previous chapter of this report, most of that earlier discussion focused on the cost of acquiring and supporting various space-based weapon systems (as well as terrestrial-based alternatives) in the absence of such countermeasures. Not all of the countermeasures noted below would, in all cases, prove cost-effective means of protecting satellites—much would depend on the specific details of the satellites to be protected, the countermeasures to be employed and the ASAT weapon thought to pose a threat. But under some circumstances, each of them could prove cost-effective. Moreover, this approach might prove especially cost-effective if some combination of these countermeasues were employed.

It is impossible, in the absence of a much more detailed analysis (perhaps including access to classified data), to estimate whether, or to what extent, the use of some combination of passive countermeasures could provide a cost-effective counter to an enemy's ASAT capabilities (or provide greater protection, at lower cost, than bodyguard satellites). However, it seems reasonable to conclude that any analysis that assumed *some* use of passive countermeasures would drive up the costs of acquiring and supporting various ASAT capabilities—above, and perhaps far above, the estimates provided in the preceding chapter.

As noted below, it is also important to understand that, just as countries with extensive and sophisticated space, and space-tracking, capabilities are likely to be able to deploy more effective ASAT weapons than countries with more primitive space-related capabilities, the former are also likely to be able to employ passive countermeasures to protect satellites much more effectively. Put another way, in many cases, passive countermeasures that might be ineffective if used against a sophisticated space-faring country could be highly effective if employed against the ASAT capabilities most likely to be acquired by countries with less developed space capabilities. Since the United States has by far the world's largest and most modern and effective network of space tracking assets, it possesses an especially important advantage in this area.

Hiding

This countermeasure involves constructing satellites with characteristics that make them more difficult to detect and track, or deploying satellites in orbits that have the same effect. In general smaller satellites are harder to detect by both passive (e.g., optical and infrared) sensors and active (e.g., radar) sensors. The detectability of a satellite can also be affected by its shape and the use of special coatings, as well as the means and frequency with which it transmits signals (which can be detected by passive sensors). In addition, a satellite's orbit can make it more or less difficult to detect. For example, operating a satellite at very low altitude can make it hard to detect using space-based infrared sensors, since such sensors must view the satellite against the relatively warm background of Earth.[226] As in many other areas, this is likely to be a significantly greater problem for countries with relatively primitive space tracking capabilities, such as Iran and North Korea, than for countries with more sophisticated space-related capabilities, and the United States in particular.

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[226] OTA, *Anti-Satellite Weapons, Countermeasures, and Arms Control,* p. 77.

Deception

Deception involves the use of decoys to confuse or overwhelm an enemy with false targets. In the case of satellites, decoys can be either inexpensive "traffic" decoys, designed to simulate only those characteristics of the satellite that can be measured and evaluated relatively cheaply, quickly and remotely, or complex decoys designed to much more closely mimic the satellite's characteristics. Traffic decoys would be far less costly to deploy than actual fully-functioning satellites. Satellites could also be designed to release simple "reaction decoys"—such as reflective balloons, clouds of smoke and chaff—upon warning of an attack.[227] Simple decoys of this type might well be effective against a country with relatively primitive space surveillance capabilities, or against guidance sensor carried aboard an ASAT kinetic-kill vehicle.

On the other hand a more complex decoy might be needed to deceive a country with relatively sophisticated space surveillance capabilities, or to deceive even a less capable adversary for an extended period or indefinitely. "The critical question is whether a decoy can be made credible at a much lower cost than that of the satellite it mimics, as well as cheaper than an enemy's cost to identify it (e.g., by launching a co-orbital interceptor to observe it at close range) or to attack it in a manner which would negate [i.e., disable or destroy] the satellite."[228]

Maneuver

Another means of defeating some ASAT weapons would be through the use of evasive maneuvers. In order to continuously evade an ASAT interceptor, a satellite must generally have an ability to accelerate and change velocity that is equal to that of the interceptor. Maximizing the maneuverability of a satellite means devoting a large fraction of the satellite's mass to its engines (for acceleration) and fuel (for velocity), and a relatively small fraction to its mission payload. Since the payload (i.e., the warhead) of an ASAT interceptor or space mine might be quite small, providing a satellite with comparable maneuverability, while possible for satellites with small payloads, might be difficult for those with large payloads. Here again, the effectiveness and cost-effectiveness of this countermeasure is likely to depend, in part, on the relative sophistication of the countries employing the countermeasure and posing the ASAT threat. Thus, for example, while

[227] Ibid., p. 79.
[228] Ibid.

it might be impractical to give a satellite the degree of maneuverability it would need to effectively avoid an advanced ASAT weapon, even a relatively small amount of maneuverability could be sufficient to essentially eliminate the probability that a simple, surface-based kinetic-interceptor armed with a pellet-cloud warhead could conduct a successful intercept.[229]

Hardening

For each type of ASAT threat there are materials and techniques that can be used to harden satellites and provide some degree of protection. However, the level of protection that hardening can provide, and the cost-effectiveness of such hardening, can vary substantially depending on the specifics of the ASAT to be countered.

As discussed in previous chapters of this report, it appears that in many cases shielding can be a relatively low-cost and effective countermeasure against laser and microwave weapons. Shielding can also provide a relatively cost-effective countermeasure to ASAT attacks designed to kill targets, out to great distances, with radiation or EMP caused by a nuclear explosion. This kind of shielding typically adds only some 2-10 percent to the cost of constructing a satellite. On the other hand, while shielding might be able to protect a satellite from tiny particles created by a relatively primitive ASAT carrying a pellet-cloud warhead, hardening does not seem to be a practical option for protecting satellites from more advanced kinetic-energy ASATs armed with homing interceptors, or nuclear-armed ASATs that detonate in relatively close proximity to the targeted satellite.

Electronic and Electro-Optical Countermeasures

These countermeasures would seek to defeat ASATs that make use of non-destructive means of interfering with satellites—such as jamming and spoofing—through various electronic and electro-optical systems and techniques. Such countermeasures include, for example, the use of greater transmitter power and signal bandwidth, or larger antennas and shorter wavelength signals, to create more jam resistant communications uplinks and downlinks.[230]

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[229] Wright et al, *The Physics of Space Security,* p. 164.

[230] Ibid, p. 82.

Proliferation—Replenishment and On-Orbit Spares

Another passive ASAT countermeasure would be to simply proliferate the number of satellites, so that even after an attack a sufficient number of satellites would remain to carry out the satellites' mission. If it were permissible to have some interruption in the performance of satellites' functions, the spare satellites could be stored on the ground and launched into orbit only when needed. On the other hand, if uninterrupted service were required the spare satellites would need to be maintained in orbit during peacetime.

This would be more costly, since satellites in orbit would have to be lifted into space and, once deployed, would be more difficult to maintain and repair. However, so long as they were dormant, the on-orbit spares might require little power generation, cooling or attitude control. In addition, dormant spares would not need to engage in radio communication as frequently as active satellites, and thus could be easier to hide. Likewise, since they would not need to expose their antenna or other sensors while dormant, these on-orbit spares could be made harder than their active counterparts.[231]

Whether the use of replenishment or on-orbit spares would prove to be a cost-effective countermeasure would depend, among other things, on the relative cost of the satellites and the ASATs designed to intercept them. It might not, for example, prove to be a cost-effective means of protecting the capabilities provided by certain large, complex and costly intelligence satellites, but could be cost-effective in the case of some types of relatively low-cost communications satellites.

This is also an area in which the relative wealth of the countries involved in such a competition could have a significant impact. Even if the cost-exchange ratio was in favor of an attacker (that is, executing a successful ASAT intercept cost less than acquiring and deploying a replacement satellite), depending on the magnitude of the advantage accruing to the attacker, for the United States and other wealthy countries, proliferating replenishment and on-orbit spares might still be a feasible option. In other words, this *might* be an area where it would be possible to simply outspend an adversary, especially poor countries like North Korea and *relatively* poor (compared to the United States) countries like Iran.

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[231] OTA, *Anti-Satellite Weapons, Countermeasures, and Arms Control,* pp. 82–83.

Proliferation—Modularization and Segregation

Another, more complex, form of proliferation would be to separate the functions of satellites into subsystems, and convert those subsystems into modules that could be deployed on different satellites.[232] In this way, the functions currently performed by a relatively small number of satellites would be spread over a much larger number of satellites. This would make the system more robust. However, segregating a satellite's subsystems and placing them on different satellites would, at least in narrow economic terms, be less efficient and lead to higher overall system costs.[233]

Reducing Dependence on Satellites

Another way to mitigate the impact of ASAT threats would be to reduce the reliance of the United States, and the US military in particular, on satellites. Most, though not all, of the functions carried out by satellites could be performed by terrestrial-based alternatives. Currently, the ASAT threats confronting US satellites appear to be more potential than actual. Moreover, it is far from self-evident that this situation will change in the near or medium term. And for many missions, satellites continue to represent less expensive and less vulnerable capabilities than terrestrial-based alternatives. Thus, it would make little sense today to begin a wholesale, and very costly, shift from satellites to terrestrial-based capabilities for the full range of functions presently performed by those space-based assets.

On the other hand, the possibility that US satellites might become substantially more vulnerable in the future (though not inevitable) is certainly real. According to Michael O'Hanlon, this danger has a number of broad implications for the US military's programming and budgeting for similar terrestrial-based capabilities.

> First, numerous airborne assets, particularly for imaging and signals intelligence, but also for targeting, guidance, and communications, should be in the force posture despite their non-trivial costs. In some cases, for assets such as P-3 aircraft and EC-135 electronic reconnaissance aircraft, refurbishment or modernization programs will be

[232] Ibid., p. 83.
[233] Ibid.

> appropriate; in others, new and less costly assets (largely UAVs) make more sense. Second, additional backup capabilities, such as fiber-optic land lines and undersea lines, should be retained in may regions of the world to permit high-volume intercontinental communications even if satellites are lost. Third, naval fleets, ground-force units, and aircraft should retain the ability to communicate internally through line-of-sight and airborne techniques, so that battle groups can always functions as single entities, even if their access to satellites is disrupted.[234]

Estimating the costs associated with the wide range of systems that may represent viable substitutes for satellite capabilities is well beyond the scope of this report. In some cases, less costly alternatives may be available. However, in other cases, the alternative systems could cost substantially, even dramatically, more. On the other hand, reducing dependence on satellite systems might provide the highest confidence solution to emerging concerns about the vulnerability of those space-based assets.

Chapter Summary and Conclusions

As noted at the outset of this chapter, the interplay between ASAT technologies and techniques and defensive satellite capabilities is complex. There is also a dearth of both unclassified analyses concerning what a constellation of bodyguard satellites might look like, and reliable, unclassified data concerning the cost and effectiveness of various passive ASAT countermeasures. As a result, no attempt was made in this chapter to generate cost estimates for a range of illustrative constellations of bodyguard satellites, or to provide even rough estimates of the likely effectiveness and budgetary costs associated with the development and deployment of various passive ASAT countermeasures.

Nevertheless, the overview of defensive satellites and passive ASAT countermeasures included in this chapter suggests some broad conclusions. First, bodyguard satellites would probably have, at best, only very limited capabilities against some of the ASAT threats most likely to emerge in coming years, including space mines, microwave weapons, and ground-based interceptors armed with nuclear warheads.

[234] O'Hanlon, *Neither Star Wars Nor Sanctuary,* pp. 129–30.

Second, space-based kinetic-energy weapons that successfully intercepted enemy space mines would create space debris that might itself destroy or damage the very satellite the defensive satellite was attempting to protect.

Third, the capabilities of defensive satellites would in many, if not most, cases be essentially indistinguishable from those of ASATs. As such, US acquisition of defensive satellites could have similar consequences in terms of escalating national rivalries and competition in space.

Fourth, passive countermeasures could substantially reduce the effectiveness of enemy ASAT capabilities, especially if a number of different countermeasures were used in combination. The effectiveness, and cost-effectiveness, of particular countermeasures or combinations of countermeasures is difficult to assess with much precision based on open source literature, and much would depend on the specific design of the ASAT and the countermeasures being employed. Nevertheless, a few generalizations can reasonably be made.

One such generalization is that, as with ballistic missile defense systems, in many cases there is a significant difference between the level of effectiveness an ASAT can (in theory) achieve in the absence of countermeasures, and what (in practice) it is likely to achieve if even relatively simple and inexpensive countermeasures are employed.

It is also true that, in general, the effectiveness and cost of the ASAT countermeasures a country would have to develop and deploy to try to protect its satellites would depend, in large part, on the extent and sophistication of the space surveillance and related capabilities possessed by both the country itself and the adversary thought to pose a threat. Thus, even relatively simple and inexpensive countermeasures might provide US satellites with a high level of protection against the kinds ASAT capabilities likely to be acquired by a country like Iran or North Korea, or even—at least for some time to come—China.

In addition, in contrast to the case with space-based ballistic missile defenses, where the advantages accruing to the attacker appear so substantial that it may be impossible for the US military to prevail by simply outspending its opponent, it is possible that the ability to draw on superior resources could have a telling effect in the case of passive ASAT countermeasures.

Taken together, these findings do not provide a compelling case for the development and deployment of bodyguard satellites over the next two decades. Indeed, the available evidence seems to suggest that employing a range of passive countermeasures may be prove to be a more cost-effective and robust means of protecting US satellites capabilities. On the other hand, as with space-based prompt-strike and ASAT capabilities—and in contrast to the case with space-based ballistic missile defense systems—it is difficult to dismiss bodyguard satellites on simple affordability and effectiveness grounds.

There may be some instances in which bodyguard satellites could prove both effective and cost-effective. It is less clear if there are many situations in which bodyguard satellites would prove more cost-effective than passive countermeasures, or whether—even to the extent such circumstances exist—it would make sense to acquire and deploy such satellites, given the possibility that doing so would spark or accelerate an arms race in space.

Report Summary and Conclusions

Questions about whether and, if so, when and what types of weapons the United States should place in space, are likely to become increasingly important in coming years. If for no other reason than because of the inevitably of further advances in, and diffusion of, technologies associated with ballistic missiles, satellites and space access, tracking and related capabilities, it is probably inevitable both that concerns will grow about the potential vulnerability of US space assets and interest will increase in the possibility of employing new kinds of space-based military capabilities.

It is impossible to answer, definitively and in advance, what the result of these trends will be. Depending upon a broad range of factors, including political considerations, the extent and type of advances that are made in relevant technologies and how the strategic environment evolves, it may or may not make sense to eventually develop and deploy space-based weapons to perform one or more of the four different missions described in this report. However, the discussion in this report indicates that *based on the best unclassified cost and effectiveness data and analysis available today*, the case for acquiring space-based weapons does not appear to be particularly compelling. That said, this report also finds that there may be substantial, and in some cases dramatic, variation in the cost and effectiveness of space-based weapons, depending on the particular mission they are intended to perform and the specifics of the system.

The case for space-based weapons appears to be weakest in the case of the boost-phase ballistic missile defense mission. A constellation of space-based weapons designed to defend the United States against an ICBM attack would be extremely costly to acquire and support. Moreover, at least based on the technology likely to be available over the next twenty years, such a system would probably not prove to be a cost-effective investment, especially when measured against the cost to a potential adversary of defeating such a system.

By comparison, space-based weapons intended to strike terrestrial-based targets could, in some cases, cost substantially less to acquire and support than space-based ballistic missile defense systems. However, such systems would likely prove more costly, and in some instances far more costly, than comparably-effective terrestrial-based alternatives.

Space-based ASAT weapons would also generally be much less costly to acquire and support than space-based ballistic missile defense systems. However, in part because the US military already possesses or is acquiring a range of terrestrial-based weapons with significant inherent ASAT capabilities, there does not appear to be a compelling need, on either cost or effectiveness grounds, to acquire a dedicated space-based ASAT capability.

Space-based defensive ("bodyguard") satellites would, to a great extent, be indistinguishable from space-based ASAT weapons. Thus, such systems would likely have similar costs. In addition, their deployment would presumably have similar implications for sparking or accelerating an arms race in space. These weapons would also be incapable of providing protection against some of the ASAT threats most likely to emerge in coming years. A more effective and cost-effective approach might be to rely on a range of passive countermeasures.

On the other hand, although this report finds that space-based weapons designed to strike terrestrial-based targets, conduct ASAT attacks, or intercept enemy ASAT weapons, may be neither necessary, nor generally as cost-effective, as terrestrial-based alternatives, it also finds that—in contrast to the case with space-based ballistic missile defenses—in a few instances, these systems may be affordable and even represent cost-effective options. In these cases, non-budgetary considerations, such as the perceived strategic importance of the capability and the potential arms race implications of moving ahead with such a system, will have to play the dominant role in shaping programmatic and policy choices.

Center for Strategic

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Assessments

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