Lasers and Missile Defense

New concepts for Space-Based and Ground-Based Laser Weapons

William H. Possel, Lt Colonel, USAF

July 1998

5

Occasional Paper No. 5
Center for Strategy and Technology
Air War College

Air University
Maxwell Air Force Base

Back to Center for Strategy and Technology

LASERS AND MISSILE DEFENSE:

NEW CONCEPTS FOR SPACE-BASED AND GROUND-BASED LASER WEAPONS

by
William H. Possel, Lt Col, USAF

July 1998

Occasional Paper No. 5

Center for Strategy and Technology

Air War College

Air University

Maxwell Air Force Base, Alabama

Lasers and Missile Defense:

New Concepts for Space-based and Ground-based Laser Weapons

William H. Possel, Lt Col, USAF

July 1998

The Occasional Papers series was established by the Center for Strategy and Technology as a forum for research on topics that reflect long-term strategic thinking about technology and its implications for U.S. national security. Copies of No. 5 and previous papers in this series are available from the Center for Strategy and Technology, Air War College, 325 Chennault Circle, Maxwell AFB, Montgomery, Alabama 36112. The fax number is (334) 953-1988; phone (334) 953-2384.

Occasional Paper No. 5
Center for Strategy and Technology
Air War College

Air University
Maxwell Air Force Base, Alabama 36112

The internet address for the Center for Strategy and Technology is:
http://www.au.af.mil/au/awc/awccsat.htm

Contents

List of Tables

Disclaimer

The Author

Lieutenant Colonel William H. Possel, USAF, has directed space system acquisitions and operations throughout his military career. Prior to the Air War College, he was Director of Production for the Titan IV space booster. His other assignments included tours with the Secretary of the Air Force for Special Projects, with responsibility for managing classified satellite technology programs and directing satellite operations at two mission ground stations. In addition, he served as a project officer for ground-based high-energy laser experiments as well as experiments on the Space Shuttle. Lt. Col. Possel has a bachelor's degree in physics from the University of Cincinnati and a master's degree in engineering physics from the Air Force Institute of Technology. He is a graduate of Squadron Officer School, Air Command and Staff College, and the Advanced Program Management Course at the Defense Systems Management College. A 1998 graduate of the Air War College, Lt. Col. Possel conducted this research under the auspices of the Center. His current assignment is the Program Manager of the Atlas space launch vehicle, Space and Missile System Center, Los Angeles Air Force Base, California.

Acknowledgements

To put together a research paper of this magnitude in less than a year would not have been possible without the support of many experts. I would like to acknowledge Dr. Dustin Johnston of the Schafer Corporation, Mr. Larry Sher, Mr. William Thompson of the Air Force Research Laboratory, Phillips Research Site, and fellow classmate Lt Col Ken Barker, all of whom graciously provided useful information and insightful comments. My Air War College faculty advisors, Dr. William Martel and Col (Ret) Theodore Hailes, gave me invaluable encouragement and assistance. My deepest thanks and appreciation go to my ever-patient family, my wife, Marie, and daughters, Angela and Therese for their support and understanding. They have continually provided me with love and understanding. That being said, I alone am responsible for any inadequacies in this paper.

Abstract

Is the Department of Defense (DOD) pursuing the correct investment strategy for space-based laser weapons? Recent advances in lasers, optics, and spacecraft technologies may bring high-energy laser weapons to a sufficient level of maturity for serious consideration as space weapons against the theater ballistic missile threat. However, these technological advances also make other architectures possible, such as the use of terrestrial laser sources with space-based relay mirrors or a mixed force of space-based lasers with orbiting relay mirrors. An important question is how these dramatic technology improvements have affected the strategic employment concepts for high-energy laser weapons.

This study presents a comparison of competing space-based architectures given the progress made with high-energy lasers, large optics, and atmospheric compensation techniques within the past several years. Three space-based architectures are evaluated against the potential ballistic missile threat: space-based lasers, ground-based lasers in conjunction with orbiting mirrors, and a combined approach using space-based lasers with orbiting mirrors. The study evaluates the technological risks and estimates the development and deployment costs. In addition, technology development programs are described for each of the architectures so that the high-risk areas will be better understood.

The conclusion of this study is that the most technologically sound and cost-effective architecture is to use space-based lasers with orbiting mirrors. This approach not only minimizes the overall technological risk but also reduces the total weight and, therefore, cost of placing these weapon systems on orbit.

I. Introduction

The United States Air Force (USAF), in conjunction with the Ballistic Missile Defense Organization, is struggling to determine the best investment strategy for space-based high-energy lasers as weapons against ballistic missiles. The debate is crucial not only because the technology has dramatically improved over the past few years, but also because defense procurement budgets continue to decline. Selecting this investment strategy presents a challenge for policy makers due to competing technical, fiscal, and political factors. The Air Force is studying only one high-energy laser architecture that uses space systems, which is the space-based laser concept. Other potential options, although not currently under consideration, consist of ground-based lasers with orbiting relay mirrors or a hybrid system using space-based lasers with orbiting mirrors. This assessment of the current laser and optics technology and an evaluation of the competing architectures will provide insights into the best investment strategy for the United States. [1]

The laser is perhaps the most important optical invention in the last several decades. Since its invention in the early 1960s, the laser has proved to be an extremely useful device not only for the scientific and commercial communities, but also for the military. At first it was considered to be "a solution without a problem," because as with many inventions, the technology appeared before the vision. Today, the laser is at the heart of an extensive array of military applications: range finders, satellite communications systems, remote sensing, target designation, and laser radar-based navigational aids.[2] The employment of laser-guided munitions in Operation Desert Storm brought new meaning to the idea of "precision engagement," and represents just one example of how the laser has shifted to become "a solution."[3] In fact, numerous countries are now developing their own laser technologies for weapons applications.[4] Since the early 1990s, lasers have demonstrated the capability to produce sufficient energy to merit serious consideration, even by the most ardent skeptics, as potential weapons against the ballistic missile threat.[5] That vision for new and smarter uses of lasers is rapidly catching up with the technology.

Today, the Air Force is proceeding with the development of the Airborne Laser (ABL) program, which is designed to acquire, track, and destroy theater ballistic missiles.[6] The USAF is committed to the ABL as the near term weapon of choice for destroying theater ballistic missiles while they are still over enemy territory. This may be the first step toward building a space-based laser weapon system.[7]

In addition to the ABL, the Ballistic Missile Defense Organization (BMDO) is funding a program to demonstrate the feasibility of a high-energy laser weapon in space. This program, the Space-Based Laser Readiness Demonstrator, which is estimated to cost $1.5 billion, is a subscale version of a proposed space-based laser weapon system for theater ballistic missile defense.[8] Congress continues to debate not only the usefulness of this concept but also its implications for the Antiballistic Missile (ABM) treaty. A number of lawmakers believe that the laser weapon provides such a valuable defense that it is worth abrogating the treaty.[9]

The underlying assumption with the current concept of laser weapons is that the entire weapon platform must be deployed in space because this is the most technologically feasible and cost-effective approach. But several other options are conceptually possible. One alternative architecture involves placing the laser device on the ground and employing optical systems, which are basically large mirrors, to relay the laser beam to the target. Another option that merits consideration entails using a combination of space-based lasers and optical relay mirrors in order to reduce the number of costly laser platforms.

A number of tough questions need to be asked and thoroughly explored. Are laser platforms orbiting the earth the most technologically realistic and cost-effective means of destroying ballistic missiles? Can the mission be achieved more efficiently with orbiting mirrors to relay the laser beam from the ground or from a smaller number of space-based lasers to the target? Are there insurmountable technological problems with any of these approaches? If these approaches are feasible, are there any remaining significant technological shortfalls and what is the most effective way of overcoming them?[10]

The purpose of this study is to conduct an independent assessment of the competing system architectures that utilize space-based assets for missile defense. The foundation of the analysis is three evaluation criteria: technological feasibility, technological maturity, and relative cost. This study also provides an overview of the ballistic missile threat and an understanding of the proliferation of missiles and missile vulnerability. The types and material characteristics of ballistic missiles determine how much laser energy is required to destroy them, and therefore the size and number of laser weapons. Following this discussion is a summary of the critical technologies required for an effective laser weapon system and what technologies have actually been demonstrated to date. The purpose is to give the reader an appreciation of how far the technology has developed and the remaining technological complexities that must be confronted.

This evaluation of the system architectures examines three alternatives for high-energy laser weapon concepts that use space assets: a space-based laser system, a ground-based laser with orbiting mirrors, and a combination of space lasers and orbiting mirrors. Based on the current missile threat and the energy required to destroy missiles, this analysis considers the requirements for each weapon constellation. Following each overview of these architectures, this study presents an analysis of the technology and technology development programs that are needed for these programs. The cost for each architecture will be analyzed with a cost model that reflects experiences with previous space mission programs, and thus will support a comparison of the relative costs of these different architectures.

The broad objective of this study is to establish a framework that will help Air Force policy makers make prudent decisions about the proper direction for funding technology development programs. This study addresses which high-energy laser weapon system concept (space-based laser, ground-based laser with orbiting mirrors, or a hybrid of fewer space-based lasers with supporting orbiting mirrors) is the most effective, technologically achievable, and affordable for the United States.

II. Evaluation Criteria

Laser weapon architecture studies conducted in the 1980s focused on defense against a massive Soviet ICBM attack, but the likelihood of this threat has significantly diminished.[11] The prominent scenario for laser weapon employment has changed from strategic defense to theater or national missile defense. Now the architectures are designed primarily to defend the US and its allies against ballistic missiles carrying weapons of mass destruction from rogue states and terrorist groups. Given these changes in the strategic challenges facing the United States, this is the right time for a new look at the options.

Technology Evaluation Criteria

This study will use a five-point scoring system, similar to the method applied today in government source selections, to evaluate the technological aspects of three space-based laser weapon architectures.[12] Although qualitative in nature, this numerical scoring system allows a relatively straightforward method of comparing the strengths and weaknesses of each concept.

One measurement looks at the technological feasibility of a concept, asking whether this technology concept violates the laws of physics, and whether it requires a significant breakthrough or is within reach of today's technology.

Table 1. Technological Feasibility Evaluation Criteria

Score	Assessment, Description
1	Violates the laws of physics, will never be possible
2	Requires multiple new breakthroughs
3	Major technological breakthroughs, challenges remain
4	No breakthroughs required, engineering issues remain
5	Minor technological and/or engineering issues remain

The other factor in the evaluation is technological maturity. If the technology is achievable, then the question is how much additional investment is required, in terms of development time, before it can be fielded. Several aspects will be considered, including the magnitude of the improvements required, the degree of integration risk, and the environmental limitations of testing these technologies in a zero-gravity environment.

Table 2. Technological Maturity Evaluation Criteria

Score	Description
1	Will require more than 15 years to develop
2	Between 10 to 15 years to develop
3	Between 5 to 10 years to develop
4	Less than 5 years to field
5	Possible to implement today

Cost Assessment Approach

At the risk of understatement, cost continues to be such a key factor in new space programs today that it strongly influences whether a program will proceed to the next stage of development. Numerous studies have examined past space programs in an attempt to understand the factors that influence the cost of these programs. Of all the factors, the three most influential are payload type, weight, and technological readiness.[13] Table 3 presents a range of costs for a variety of space systems.

Table 3. Range of Costs for Space Systems[14]

Type of Space System	Typical Range of Specific Cost ($K/kg)
Communication Satellites	70 - 150
Surveillance Satellites	50 - 150
Meteorological Satellites	50 - 150
Interplanetary Satellites	>130

The two previous tables on evaluation criteria focused on technological feasibility and maturity. A cost estimate for high-technology space programs must consider special factors that relate to technological readiness. One significant cost factor that past high-technology programs have experienced is the fact that technological risks increase program costs. How much the costs actually increase depends on the extent to which the technology has been demonstrated and tested in a space environment.[15]

Table 4. Levels of Technological Readiness[16]

Readiness Level	Definition of Readiness Status	Added Cost
1	Basic principle observed	25%
2	Conceptual design formulated	25%
3	Conceptual design tested	20-25%
4	Critical function demonstrated	15-20%
5	Breadboard model tested in simulated environment	10-15%
6	Engineering model tested in simulated environment	<10%
7	Engineering model tested in space	<10%
8	Fully operational	<5%

An additional cost is that of placing the platform in orbit because launch costs, especially for space lasers, are likely to be a significant factor. The cost of transporting a satellite into low earth orbit ranges from $9,400 to $32,400 per kilogram.[17] The Space Shuttle and Titan IV are in the class of the launch vehicles that are required to put space-based laser platforms into orbit. For these launchers, the cost for putting low-earth payloads into orbit is $11,300 and $18,400 per kilogram, respectively.[18] The typical costs for geosynchronous earth orbits are $14,000 to $30,800 per kilogram,[19] but these costs may be reduced by as much as fifty percent with the Air Force's proposed Evolved Expendable Launch Vehicle.[20]

While higher fidelity cost models for space systems are available, these are beyond the scope of this paper.[21] Therefore, the crucial aspect of this discussion is the relative cost comparison of the three architectures, which for this purpose will be based solely on weight, technological readiness, and launch costs.* Before examining the different laser systems, the next section examines the ballistic missile threat and the vulnerabilities of ballistic missiles as part of an evaluation of these alternative architectures.

---

* The costs estimates in this paper do not include mission operations and refueling or replacing the satellites. A rule-of-thumb is that these costs run between 10 to 25 percent of the total program costs.

III. Ballistic Missile Vulnerabilities

Desert Storm highlighted the significant threat posed by ballistic missiles, particularly to our allies, and perhaps to the United States in the future. Even though Iraqi missiles were inaccurate and conventionally armed, these weapons created a significant menace and had significant political effects on the conduct of the war.[22] Today, there is a significant danger of ballistic missiles carrying weapons of mass destruction given the number of rogue states that are developing missile technology as well nuclear, chemical, and biological weapons. According to the testimony of a science advisor to former President Reagan before the Senate Governmental Affairs subcommittee on proliferation, "Today, opportunities for developing countries to acquire long-range ballistic missiles are at an all-time high."[23] Not only do well-developed countries such as China, Russia, and France possess missiles, but smaller countries also are either developing the technology or importing ballistic missiles.

Missile Threats

Ballistic missiles appear to be the preferred weapon for rogue countries to terrorize neighboring states. These countries observed the effect that the Iraqi ballistic missiles had on the coalition forces during Desert Storm, particularly in nearly drawing Israel into the war. Even though most of the missiles are inaccurate and have a relatively low military utility, to rogue states they present an attractive means of intimidating neighboring countries without the large costs required for conventional forces. It is also a matter of prestige and a symbol of national power both inside and outside of their country.

Missiles can hit their targets, usually cities, within minutes of launch, are relatively inexpensive and, until Desert Storm, do not face active defenses.[24] Some 36 countries have been identified as possessing ballistic missiles of some type, and 14 nations have the capability to build them.[25] These missiles, which range in size from large intercontinental ballistic missiles (ICBMs) to small Scud missiles, are dispersed worldwide.

The world's major powers possess the most technologically advanced missiles. While Russia and China both possess ICBMs capable of striking North America, the threat of either country launching such an attack against the U.S. is extremely low. India has developed a space-launch vehicle that could be modified for use as an ICBM.[26] These programs fuel concerns that these countries might provide assistance to other nations that seek to develop new ballistic missiles.[27]

There is increasing concern with the rapid proliferation of short-range ballistic missiles (SRBMs) and medium-range ballistic missiles (MRBMs). North Korea's Scud Bs and Scud Cs, both of which are short-range missiles, could easily hit cities in South Korea and Japan. North Korea is also developing the Taep'o-dong II missile with a range estimated between 7,500 kilometers and 10,000 kilometers. With a range of 7,500 kilometers, the Taep'o-dong II could reach Alaska or Hawaii, and if the longer-range estimate is correct, these missiles could strike the western reaches of the continental United States.[28] Some experts predict the missile may be operational by the year 2000.[29]

Missile technology is a profitable export item for several nations. A number of countries are willing to export complete systems, technologies, and developmental expertise for the income that is generated by foreign sales. China, North Korea, and several industrialized states in Europe are supplying ballistic missiles and missile-related technologies, which further increases the number of nations with ballistic missile capabilities.[30] Iran possesses submarine launched cruise missiles (SLCMs) through its purchases of Kilo class submarines from Russia. The United Nations has attempted to curtail the sale of missile technology through the Missile Technology Control Regime (MTCR).[31]

The addition of weapons of mass destruction to a missile's warhead radically increases the threat. Ballistic missiles that are armed with nuclear, chemical, or biological warheads could provide nations with an effective tool for conducting asymmetric warfare. Following Desert Storm, rogue states realized that ballistic missiles have great political significance, especially since they are becoming readily available and are being combined with weapons of mass destruction. This combination adds a new dimension to the threat to the United States and its allies.[32]

An additional problem is that India, Pakistan, and several Middle Eastern countries have refused to sign the Nuclear Nonproliferation Treaty (NPT), and are suspected of exporting nuclear technology. While China adheres to the treaty, it has not adopted the export policies of the Nuclear Suppliers Group and continues to sell nuclear energy and research-related equipment to countries with nuclear weapons programs.[33] Many countries have offensive chemical weapons programs; the most aggressive of which are Iran, Libya, and Syria, all of which refused to sign the Chemical Weapons Convention (CWC).[34] A summary of ballistic missile proliferation is shown in Table 5.

Table 5. Ballistic Missile Capabilities by Country[35]

	SRBM	MRBM	IRBM	ICBM	Cruise Missile	Nuclear	BW	CW	NPT	CWC	MTCR
Argentina	X				X	Capability			X	X	X
Belarus	X			X	X	X			X	X	
Brazil	X					Capability				X	X
China	X	X	X	X	X	X	X	X	X	X	
India	X		X		X	X	X	X		X	
Iran	X	X			X	Develop	X	X	X	X	
Iraq	X	X			X	Develop	X	X	X		
Libya	X				X		X	X	X		
N. Korea	X	X	Develop				X	X	X		
Russia	X	X	X	X	X	X	X	X	X	X	X
Syria	X	X					X	X	X		
Ukraine	X			X	X	X			X	X	

In view of this growing threat to the United States, the DOD, with strong support from Congress, is pursuing a number of defensive systems that are designed to counter these missiles. The Ballistic Missile Defense Organization is developing a family of missile defense systems for the specific purpose of defeating ballistic missile attacks. In view of the diversity of missiles owned by countries that are hostile to the United States, there is a growing realization that no single system can accomplish the entire mission. What is emerging is an integrated approach in which the United States is designing lower-tier defenses to intercept missiles at low altitudes within the atmosphere and upper-tier systems to intercept missiles outside the atmosphere and at long ranges. The Army's Patriot system, which was used during Desert Storm, demonstrated the political and military value of a lower-tier ballistic missile defense.[36] A high-energy laser is a potential weapon for the upper-tier defense.

Ballistic Missile Vulnerabilities from Lasers

The view in DOD is that high-energy laser weapons represent the most promising response to the increased threat posed by ballistic missiles.[37] Unlike the larger intercontinental ballistic missiles, the fact that small ballistic missiles are constructed with lighter weight materials and thinner outer skins increases their vulnerability to laser weapons. Indeed, a laser beam is probably the ideal instrument for destroying a ballistic missile. With its tremendous speed, lack of recoil, and extremely long range, the laser offers the potential to destroy missiles during the boost phase, which would have the added benefit of keeping possible nuclear, biological, or chemical warheads on the enemy's side of the border.

The key factor in designing a cost effective weapon architecture is determining the exact amount of laser energy required to destroy a missile. In order for a laser weapon to destroy a ballistic missile, the missile skin must be heated, melted, or vaporized. For a laser to disable a missile, it must concentrate its energy on certain parts of the missile and hold the beam steady for a long enough time to heat the material to the failure point. The effectiveness of the laser depends on the beam power, pulse duration, wavelength, air pressure, missile material, missile velocity, and the thickness of the missile's skin.[38] If the laser could specifically target the electronic circuits, which are used for guidance control, it would render the missile incapable of staying on course.[39] These circuits are relatively easy to destroy but difficult to target precisely. Another kill mechanism is to melt a section of the material surrounding the missile's fuel tank and detonate the fuel. A third and more realistic approach is to heat the missile skin until internal forces cause a failure of the skin around the fuel tank. This type of failure produces a rupture of the missile given the enormous internal pressure in the fuel tank. It also requires the least amount laser energy to destroy the missile.[40]

How much energy is required to rupture the skin of a missile depends on the material and thickness of the missile skin.[41] Table 6 presents a list of different ballistic missiles with their range, burn time, skin material, and skin thickness. The energy from the laser must be focused on the target long enough for the skin material to absorb the radiation and cause the missile fuel tank to rupture before the heat dissipates. A general value for this energy (called "lethal fluence") is one kilojoule per square centimeter, although the exact fluence value varies slightly for each missile.[42]

Table 6. Missile Vulnerability Parameters[43]

Name/Country of Missile	Range (km)	Missile Burn Time (sec)	Material	Thickness (mm)
Scud B (Russia)	300	75	steel	1
Al-Husayn (Iraq)	650	90	steel	1
No Dong-1 (North Korea)	1000	70	steel	3
SS-18 (Russia)	10,000	324	aluminum	2

This table illustrates some of the parameters required to determine the exact amount of energy that must be absorbed by the missile to cause a structural failure. If one calculates that the missile skin has ninety percent reflectivity (meaning that only ten percent of the laser energy on target is absorbed), the laser fluence on the missile would need to be ten times greater.[44] Yet, laser weapons will be required to produce even greater amounts given the energy that is lost to atmospheric absorption, thermal blooming, laser beam jitter, and pointing errors.

IV. Current State of Laser Weapon Technology

By virtue of their ability to destroy a missile at the speed of light, high-energy lasers are extremely attractive weapons against ballistic missiles. With the development of the first lasers in the early sixties, military scientists have been pushing laser technology to achieve greater laser power, better optics, and improved target acquisition, tracking, and pointing technologies. The next section presents an overview of the current state of laser weapon technologies that are critical to understanding the technological risks that are associated with fielding any laser weapon system.

Lasers

In 1917, Albert Einstein developed the theoretical foundation of the laser when he predicted a new process called “stimulated emission.” It was not until 1958 that A. Schawlow and C. H. Townes actually built a device that utilized this theory and successfully exploited Einstein's work. Following the birth of the first laser, a myriad of lasers with different lasing materials and wavelengths were rapidly developed. All of the lasers that are under consideration for weapons applications were designed and built in the pioneering days of the laser that occurred between the early 1960s and into the late 1970s.[45]

Three laser systems are being considered for space-based and ground-based laser weapons. These are all chemical lasers and involve mixing chemicals together inside the laser cavities to create the laser beam. Chemical reactions create excited states of the atom or molecule and provide the energy for the laser.[46] The competing lasers are hydrogen fluoride (HF), deuterium fluoride (DF), and chemical oxygen iodine (COIL).

Hydrogen Fluoride Laser. The hydrogen fluoride laser operates much like a rocket engine. In the laser cavity, atomic fluorine reacts with molecular hydrogen to produce excited hydrogen fluorine molecules. The resulting laser produces several simultaneous wavelengths in the range of 2.7 microns and 2.9 microns. The laser beam, at these wavelengths, is mostly absorbed by the earth's atmosphere and can only be used above the earth's atmosphere.[47] This laser is the leading contender for the Space-Based Laser (SBL) program.

he Ballistic Missile Defense Organization continues to support the hydrogen fluoride laser for space-based defenses.[48] The Alpha program, originally funded by Defense Advanced Research Projects Agency (DARPA) in the 1980s, then the Strategic Defense Initiative Office (SDIO), and now BMDO, has successfully demonstrated a megawatt power laser in a low-pressure, simulated space environment.[49] The design is compatible with a space environment, is directly scalable to the size required for a space-based laser, and produces the power and beam quality specified in the SDIO plan in 1984.[50] This laser has been integrated with optical systems from the Large Advanced Mirror Program, described later, and has been test fired at the TRW San Juan Capistrano test facility in California.[51]

Deuterium Fluoride Laser. The deuterium fluoride laser operates on the basis of the same physical principles as the hydrogen fluoride laser. Rather than molecular hydrogen, deuterium (a hydrogen isotope) reacts with atomic fluorine. The deuterium atoms have a greater mass than hydrogen atoms and subsequently produce a longer wavelength laser light. The deuterium fluoride laser wavelengths, 3.5 to 4 microns, provide better transmission through the atmosphere than the hydrogen fluoride laser.[52] However, the principal drawback of the longer wavelength is that larger optical surfaces are required to shape and focus the beam. This type of laser has been refined and improved since the 1970s.

The Mid-Infrared Advanced Chemical Laser (MIRACL), built by TRW Inc., is a deuterium fluoride laser that is capable of power in excess of one megawatt.[53] The system was first operational in 1980 and since then has accumulated over 3,600 seconds of lasing time.[54] This laser system has been integrated with a system called the SEALITE Beam Director, which is a large pointing telescope for high-energy lasers, and in 1996 successfully shot down a rocket at the U.S. Army's High-Energy Laser Systems Test Facility at the White Sands Missile Range.[55]

Chemical Oxygen Iodine Laser. Another relatively new and promising laser, the chemical oxygen iodine laser, or COIL, which was first demonstrated at the Air Force Weapons Laboratory in 1978. The lasing action is achieved by a chemical reaction between chlorine and hydrogen peroxide that produces oxygen molecules in an electronically-excited state. Excited oxygen molecules transfer their energy to iodine atoms by collisions, which raises the iodine atoms to an excited state. The excited iodine atom is responsible for lasing at a wavelength of 1.3 microns, which is shorter than the output of the hydrogen fluoride or deuterium fluoride laser. One significant advantage of this laser is that the shorter wavelength allows for smaller optics than the other lasers.[56] In addition, this wavelength of light transmits through the atmosphere with less loss from water vapor absorption than the hydrogen fluoride laser.[57] These advantages have accelerated the funding and development of the COIL.

This laser, which was selected by the Air Force for the Airborne Laser missile defense system, will be placed in the rear of a 747 to serve as the "killing" beam against theater ballistic missiles. A test of the COIL conducted by TRW in August 1996 produced a beam with power in the range of hundreds of kilowatts that lasted several seconds.[58]

Optics

No matter how powerful a laser is, it will never reach its target without optical components. The optical components not only "direct" the beam through the laser to its target, but they also relay the laser energy and, when required, correct for any atmospheric turbulence that will distort the beam. The tremendous advances in optics have played a key role in convincing the Air Force that laser weapon systems can be produced. Without these successes by government laboratories and industry, high-energy laser weapons would be impossible.

Adaptive Optics. The reason stars twinkle in the night sky is due to atmospheric turbulence, which also will distort and degrade any laser. This effect has especially severe effects for the shorter wavelength lasers, such as COIL.[59] These systems require sophisticated optics in order to "pre-compensate" the laser beam for atmospheric turbulence.[60] To pre-shape the laser beam, an adaptive optics technique is used. Over the past several years, the Air Force Research Laboratory, Phillips Research Site, and the Massachusetts Institute of Technology's Lincoln Laboratory have made significant strides in adaptive optics.[61]

The principle behind adaptive optics is to use a deformable mirror to compensate for the distortion caused by the atmosphere. The system first sends out an artificial "star" created by a low power laser. When that laser beam is scattered by the atmosphere, the scattering radiation is reflected back and measured so that the system knows just how much the atmosphere is distorting the laser. By feeding this information into a complex control system, the deformable mirror, with its hundreds of small actuators positioned behind the mirror, alters the surface of the mirror to compensate for atmospheric distortion. Thus, a high-energy laser can be "pre-distorted" so it will regain its coherence as it passes through the atmosphere.[62]

The Starfire Optical Range at the Phillips Research Site has successfully demonstrated the adaptive optics technique. It has a telescope with the primary mirror made of a lightweight honeycomb sandwich, which is polished to a precision of 21 nanometers, or approximately 3,000 times thinner than a human hair. To compensate for the distortion caused by gravity, the primary mirror has 56 computer-controlled actuators behind its front surface to maintain the surface figure. The 3.5-meter telescope adaptive optics system has a 941-actuator deformable mirror that is controlled by a complex computer system.[63] What has been accomplished at the Starfire Optical Range represents possibly the most significant revolution in optical technology in the past ten years.[64]

Large Optical Systems. In addition to adaptive optics, large mirrors, either on the ground or in space, are needed to expand and project the laser energy onto the missile. Several significant large optics programs were conducted in the late 1980s and early 1990s. The Large Optics Demonstration Experiment (LODE) established the ability to measure and correct the outgoing wavefront of high-energy lasers.[65] The Large Advanced Mirror Program (LAMP) designed and fabricated a four-meter diameter lightweight, segmented mirror.[66] This mirror consists of seven separate segments that are connected to a common bulkhead. The advantages of building a mirror in segments are to reduce the overall weight and fabricate larger mirrors. In addition, each segment can be repositioned with small actuator motors to slightly adjust the surface of the mirror. The program's finished mirror successfully achieved the required optical figure and surface quality for a space-based laser application.[67]

Acquisition, Tracking, Pointing, and Fire Control

Directing the laser energy from the optics to the target requires a highly accurate acquisition, tracking, pointing, and fire control system. A laser weapon system, either space-based or ground-based, needs to locate the missile (acquisition), track its motion (tracking), determine the laser aim point and maintain the laser energy on the target (pointing), and finally swing to a new target (fire control). The accuracy for each component is stringent because of the great distances between the weapon and the targets.[68]

The United States put considerable time and resources into both space and ground programs in acquisition, tracking, and pointing technologies. Space experiments are critical to any high-energy laser weapon system because they demonstrate the high-risk technologies and do so in the actual operational environment. However, the space programs in the 1980s suffered from high costs and the space shuttle *Challenger* accident.[69] While many programs were terminated or had their scope reduced due to insufficient funding, two highly successful space experiments were completed in 1990. The Relay Mirror Experiment demonstrated the ability to engage in high accuracy pointing, laser beam stability, and long duration beam relays. This is a critical technology for any weapon architecture that requires relay mirrors in space. Another successful test was the Low Power Atmospheric Compensation Experiment that was conducted by the MIT Lincoln Laboratory, which demonstrated the feasibility of technologies that are designed to compensate for the atmospheric turbulence that distorts laser beams.

A number of the space experiments were canceled or redesigned as ground experiments. Ground experiments can be successfully conducted as long as the tests are not limited or degraded by the earth's gravity. Two ground experiments demonstrated the key technologies that are essential for the space weapon platform to maintain the laser beam on the target despite the large vibrations induced by the mechanical pumps of a high-energy chemical laser.[70] The Rapid Retargeting/Precision Pointing simulator was designed to replicate the dynamic environment of large space structures. Using this technology, which is especially critical for a space-based laser, scientists tested methods to stabilize the laser beam, maintain its accuracy, and rapidly retarget. Within the constraints of a ground environment, the techniques developed should be applicable to space systems.[71]

Another successful experiment was the Space Active Vibration Isolation project, which established a pointing stability of less than 100 nanoradians. This equates to four inches from a distance of 1000 kilometers. The Space Integrated Controls Experiment followed that program and further improved the pointing stability.[72] To understand the technology necessary to control large structures, such as space mirrors, the Structure and Pointing Integrated Control Experiment (SPICE) was developed to demonstrate the value of active, adaptive control of large optical structures.[73] These tests, experiments, and demonstrations represent the current state-of-the-art in laser technology, which leads to the question of how to fit these technologies into an architecture and how much further to push the technology.

V. Space-Based Laser Architecture

A space-based weapon system possesses unique capabilities against ballistic missiles. It has the distinct advantage over ground systems of being able to cover a large theater of operations that is limited only by the platform's orbital altitude. As the platform's altitude increases, the size of the area it “sees” increases. Ultimately, if the platform is orbiting in a geosynchronous orbit, it can provide coverage of nearly half the earth's surface. Alternatively, if a laser is deployed in low-earth orbit, it decreases the distance from the laser to the missile, and yet increases the number of weapon platforms that are required to provide global coverage. Each alternative presents a range of strengths and weaknesses as those pertain to effectiveness, technological feasibility, and cost.

The concept of space-based laser (SBL) weapons has been contemplated since the 1970s. SBLs have been considered for offensive and defensive satellite weapons as well as ICBM defense.[74] The original Strategic Defense Initiative (SDI) architecture was designed to destroy the Soviet Union's ICBMs in the boost phase before the deployment of independently-targeted re-entry vehicles or warheads. As an example of a Strategic Defense Initiative-type scenario, a study suggested that if the Soviets attacked with 2,000 ICBMs, all launched simultaneously, the system would be required to kill 40 missiles per second. This threat drove the space-based laser platform's requirements to a 30 megawatt laser and a ten-meter diameter primary mirror.[75]

Following the collapse of the USSR and the reduced risk of nuclear war, space-based laser concepts have been redirected to defend against theater ballistic missiles. Rather than concentrating on a large number of long-range missiles launched from the Soviet Union, the focus for laser systems is to destroy short-range missiles launched from anywhere in the world. This change in the threat significantly reduces the requirements for laser weapons below that which was outlined in the SDI scenarios in the 1980s.[76]

Operational Concept

The BMDO has completed several space-based laser architecture studies of the orbital altitude, power, optics requirements, and the number of platforms for laser weapons. It has determined that the best concept is a system of twenty space-based laser platforms that operate at an inclination of 40 degrees, 1,300 kilometers above the surface of the earth. In this orbit, the space-based laser can destroy a missile in approximately two to five seconds, depending on the range of the missile. Each laser can retarget another missile in as little as one-half second if the angle between the new target and the laser platform is small. The space-based laser will be capable of destroying a missile within a radius of 4,000 kilometers of the platform. The initial deployment will consist of twelve platforms for partial coverage of the earth, and move eventually toward a constellation of twenty satellites that will provide nearly full protection from theater ballistic missile attacks.[77]

Each space-based laser platform will consist of four major subsystems: a laser device, optics and beam control system, acquisition, tracking, pointing and fire control (ATP/FC) system, and associated space systems. The laser device will be a hydrogen fluoride laser that operates at 2.7 microns. A primary mirror, with a diameter of eight meters, will utilize super-reflective coatings that will allow it to operate without active cooling, despite the tremendous heat load from the laser energy.[78] One estimate for the laser power is eight megawatts.[79] The fire control system includes a surveillance capability and a stabilized platform to maintain the beam on the target despite the jitter produced by the mechanical pumps of the high-energy laser. The associated space systems provide the necessary electrical power, command and control, laser reactants, and on-board data processing. The estimated weight of each space-based laser is 35,000 kilograms.[80] For comparison, the Hubble Space Telescope is 11,000 kilograms and Skylab was 93,000 kilograms.[81]

Architecture Evaluation

The space-based laser concept has to overcome several significant technological and operational challenges, many of which will be addressed with an on-orbit demonstration system. The operational concerns are related to its on-orbit logistics. Since the laser is chemically fueled, the space-based laser is only capable of a limited number of shots before its fuel is depleted. The current concept calls for 200 seconds of total firing time. With this much fuel, the space-based laser is capable of at least 75 shots against typical theater ballistic missiles. When the fuel is expended, the space-based laser must be either refueled in space or replaced.[82] Another potential hurdle is getting these platforms into space.

Technology Assessment. While individual pieces of technology have been developed, to date no such system has been integrated and demonstrated. The Alpha program demonstrated a hydrogen fluoride high-energy laser, which could be scaled up to the power levels required for an operational laser. In the case of optical components, the Large Optics Demonstration Experiment and Large Advance Mirror Program verified critical design concepts for large optics and beam control, but at only half the size of the operational laser. Several other programs described earlier proved the ability to accurately acquire, track, and point large structures.

One significant remaining question is whether all of these systems can be effectively integrated into a space platform. An on-orbit demonstration of an integrated system addresses those issues. The Space-Based Laser Readiness Demonstrator (SBLRD) is a proposed half-scale version of the operational laser platform. This demonstrator offers the potential to reduce the risks associated with fielding such a complex entity by integrating the various subsystems into a space-qualified package.[83] The system will consist of a high-energy hydrogen fluoride laser operating at one-third the output power of the operational laser. The acquisition, tracking, and pointing subsystem and the laser beam will not operate concurrently since this may violate the ABM treaty. At an estimated weight of 16,600 kilograms, which is slightly more than half the operational weight, the laser demonstrator will be launched on the Titan IV booster or the new Evolved Expendable Launch Vehicle. On-orbit tests will consist of deploying large target balloons to test the accuracy of the laser tracking and pointing subsystem. In addition, rockets with sensors will be launched as test vehicles. The test program, if we optimistically assume a launch date of 2005, will span three years. [84]

If the laser demonstrator comes to fruition, the maturity and feasibility of the space-based laser program will be significantly enhanced. The previous technology programs have demonstrated that most of the basic engineering obstacles can be overcome. The remaining concerns for the platforms are system engineering, integrating the subsystems, and demonstrating that they can work together in a space environment. The engineering that is required for the laser demonstrator would address most aspects of the laser platform. All of these steps are essential before the US can commit to develop a space-based laser system.

Another significant challenge facing the program is the launch vehicle for the full-scale platforms. The next generation launch booster, the follow-on to the Titan IV, will have the same capacity to place a payload of 22,000 kilograms into low earth orbit.[85] If the dimensions of the laser platform cannot be reduced, this limit on payload size will require that each laser platform is launched on two rockets and assembled in space, or for the development and fielding of a new class of launch vehicles. However, a new launch vehicle developed specifically for the space-based laser is not a likely option in view of how long the DOD has been trying to replace the Titan IV.[86] Assembling a large system such as a space-based laser in space has never been tested. Further studies are required to consider alternatives to reduce the weight or demonstrate the feasibility of assembling the system in space. For this reason, the assessment for the launch received a lower rating than the other subsystems. Furthermore, the maturity ratings for integration were based on a laser demonstrator launch in 2005 with final results by 2008.

Table 7. Space-Based Laser Architecture Technological Assessment

Systems	Feasibility	Maturity
High-Energy Laser	4 (no breakthroughs required)	4 (less than five years to field)
Optical Components	4 (no breakthroughs required	(less than five years to field)
ATP/FC	4 (no breakthroughs required)	(less than five years to field)
Integration	3 (major challenges remain)	(ten to fifteen years to field)
Launch	3 (major challenges remain)	(ten to fifteen years to field)

Note: This assessment assumes the successful development of a space-based laser readiness demonstrator.

Cost Estimate. Numerous government agencies and contractors have analyzed the program costs for the past 15 years. Recently, three independent cost estimates were conducted: a space-based laser contractor in response to an inquiry from the Chairman of the Senate Armed Services Committee (Senator Thurmond); a BMDO internal program office estimate; and the BMDO Capstone Cost and Operational Effectiveness Analysis (COEA) cost estimate. These estimates predicted that the cost could range from \$17 billion to \$29 billion for 20 platforms, including the work required for the remaining development efforts.[87]

In comparison with other advanced space programs, these cost estimates for the space-based laser are exceptionally low and probably unrealistic. Based on the experience with previous programs, the average cost of military satellites ranged from \$50,000 to \$150,000 per kilogram. In the case of the proposed space-based laser architecture, the entire constellation's estimated weight is 700,000 kilograms (twenty platforms at 35,000 kilograms each). Using this historical "average" cost of \$100,000 per kilogram for the development of a space system, the costs for the platforms are likely to be in the range of \$70 billion. Assuming that the laser demonstrator has been successfully tested in space, the technological readiness level, described in an earlier section, is rated as a 7, which effectively increases the cost estimate by ten percent. When launch costs are included, based on the new launch vehicle's proposed costs of \$5,650 per kilogram, the total cost rises to \$81 billion.* Using this rough estimate, we now have a means for comparing the space-based laser architecture with the following two competing architectures.

Technology Development Programs

Although the space-based laser components are relatively mature, several new technologies offer significant opportunities to reduce the size, cost, and weight of the laser platform. The objective in the near term must be to focus resources on the laser demonstrator because it is extremely risky to deploy this weapon system without a successful demonstration of a high-energy laser weapon system in space. The various technologies in a space-based laser have been studied and tested since the 1970s, which implies that any remaining uncertainties exist in the system engineering aspects of building a space-worthy platform.

Investments in several key technologies could improve the performance and reduce the cost of the space-based laser, most notably in the areas of shorter wavelength lasers, larger optics, and improved pointing and tracking. Shorter wavelengths would allow for smaller and lighter optics. Various other laser candidates are possible to replace the hydrogen fluoride laser and produce a shorter wavelength, which includes a derivative of the hydrogen fluoride laser that operates at a wavelength of 1.3 microns.[88] A second alternative is the Chemical Oxygen Iodine Laser that also operates at 1.3 microns and is being pursued by the Airborne Laser program office. New diode lasers are being studied that would combine numerous beams to produce high power outputs at a wavelength as low as 0.8 microns.[89]

In addition to improving lasers, advancing the state of the art in optics is another area of potentially high payoffs. If the laser beam director had a larger primary mirror, the amount of fluence delivered on the target would increase. A larger mirror could focus the laser beam down to a smaller spot size and increase the laser intensity. In return, the laser power output could be reduced, which would save weight and potentially reduce costs.[90] Large optical systems are described in depth in the following section.

The final area for additional investment is in the pointing and tracking technology. Improvements in pointing accuracy would decrease the amount of "smearing" caused by beam jitter, which has the same effect as larger optics or more powerful lasers. Improved pointing could be accomplished by a variety of means. In any case, detailed analyses will identify where to focus efforts for improving pointing accuracy.

---

* The following methodology was used to calculate the cost estimate for the SBL architecture:
1. SBL development cost = SBL total weight x cost per kilogram
= 700.000kg x \$100,000/kg
$= \$70.0 \text{ x}10^{9}$
2. Added cost for level of technical readiness = development cost x 10%
$= (\$70.0 \text{ x } 10^{10}) \text{ x } 0.10$
$= \$7.0 \text{ x } 10^{9}$
3. Launch cost = SBL total weight x cost per kilogram to orbit
= 700.000 kg x \$5650/kg
$= \$3{,}955 \text{ x } 10^{9}$
4. Total cost = development cost + added cost for technological readiness = launch cost
$= (\$70.00 \text{ x } 10^{9}) + (\$70.0 \text{ x } 10^{9}) + \$3{,}955 \text{ x } 10^{9})$
= \$80.955 x 109 or about \$81 billion

VI. Ground-Based Laser Architecture

A second major alternative to destroying theater ballistic missiles with laser weapons is to place the laser on the ground and relay the beam to the missile with large mirrors in space. The distinct advantage of this architecture is that the high-energy laser is kept on the ground, which eliminates the need to fit a laser platform onto an existing launch vehicle and the need to refuel the laser weapon's chemicals in space. In addition, the complex and maintenance-intensive equipment, i.e. the laser, fuels, and pumping systems, are left on the ground. If problems develop with the ground laser systems, the equipment is readily accessible without the need for planning, funding, and recovering satellites from orbit. A further benefit is that the ground laser and beam director are not as constrained by diameter, weight, or volume as is the case for a space platform that must fit within a launch vehicle.

Unlike the space-based laser architecture, the ground-based laser system concept utilizes large optical systems in space to pass the laser beam from a ground laser to the ballistic missile. However, as with the space-based laser, the ground-based laser concept evolved during the Strategic Defense Initiative era, but received far less emphasis than the space-based laser system given the technological challenges involved with this architecture.[91] The earlier-cited Strategic Defense Initiative-type scenario for the ground-based laser system suggested that the system would be required to kill 40 missiles per second, if the Soviets attacked with 2,000 simultaneously launched ICBMs. This scenario drove the architecture requirements for at least 150 ground telescopes and 50 powerful ground lasers.[92] Since then the threat has changed dramatically and so have the technologies. This section presents an architecture that is based on this reduced threat and an evaluation of the technological feasibility, maturity, and cost of this operational concept.

Operational Concept

The ground-based laser architecture consists of multiple ground stations with high-energy lasers placed in different regions of the country. This system includes the laser and two types of space-based optical components: the relay mirror and the mission mirror. For the laser beam to be transmitted through the atmosphere without significant power losses due to absorption, the ground laser most likely would be either a deuterium fluoride or COIL type device. For reference, the problem with a hydrogen fluoride laser is that at its wavelength the laser beam is largely absorbed by the atmosphere.

Since poor weather, such as clouds, wind, and pollution, can distort the laser beam, the ground-based lasers must be located in regions that have good weather year round. A study on laser communications determined that to achieve 99.5 percent availability due to weather conditions, five sites are required, which translates into fifty minutes of poor weather per week at all five sites simultaneously. Typical sites are in the southwest United States, such as California, Arizona, and New Mexico.[93]

Each of the five ground systems would include a high-energy laser, beam director, adaptive optics, acquisition and tracking systems, and related support systems. Of the two possible options in the near-term for the high-energy laser, deuterium fluoride or Chemical Oxygen Iodine Laser (COIL), the COIL is the preferred laser given the advantages associated with its shorter wavelength. But the key question is whether the laser can achieve the necessary energy level. For the ground-based laser concept, the required energy of the laser would need to be substantially greater than the space-based laser, principally because of greater losses due to atmospheric transmission, thermal blooming, and the longer ranges that the beam must travel.

The ground laser would be integrated with a beam director in a fashion that resembles the previously-discussed SEALITE system. Similar to the new large astronomical telescopes, the beam director would have an “active” primary mirror formed by independent mirror segments mounted on mechanical actuators to maintain the optical figure.[94] It would also include a multiple-actuator deformable mirror that operates at high bandwidth to compensate for atmospheric distortion, which is analogous to the adaptive optics system at the Starfire Optical Range. It is worth noting that the technology demonstrated at Starfire overcame one of the fundamental problems with a ground-based laser system.

From the beam director, the laser beam is transmitted through the atmosphere to a constellation of mirrors in space. Changes in the altitude of the space mirrors will affect the diameter required for the beam director's primary mirror, relay mirrors, and mission mirrors, and as well as the number of space mirrors. As an example of just one of many technical and operational tradeoffs, the relay mirror could be positioned in geosynchronous, highly elliptical, or medium earth orbits, where it would “catch” the laser beam and then relay it to the mission mirror.

While a geosynchronous or highly elliptical orbit would require a larger diameter relay mirror than the medium earth orbit, at geosynchronous orbit the number of mirrors required to “cover” the world is so much less than medium earth orbit that it effectively reduces the complexity of the laser system. For this architecture, a total of four relay mirrors in geosynchronous orbit would provide the necessary worldwide coverage. One of these mirrors would be positioned as close as possible to the zenith of the ground lasers to minimize atmospheric effects.[95]

Since the mission mirror must receive the incoming laser beam from the relay mirror and then focus the beam onto the target, the mission mirrors would be in low earth orbit. This option reduces the diameter of the mission mirror and produces a correspondingly smaller laser spot on the intended target. As with the relay mirrors, the parameters of the mission mirror depend on a number of factors, including the laser wavelength, relay mirror diameter, mission mirror diameter, and altitude of each mirror.[96]

One particularly intriguing concept for the mission mirror is known as a bifocal mirror. Consisting of two connected telescopes, this system is coupled by smaller mirrors that transfer the beam from the receiving telescope to the transmitting telescope. The first telescope, the incoming receiver, is pointed directly at the relay mirror so that the laser beam is received directly into the primary mirror. This design reduces the loss of laser power from incidence angles that are less than 90 degrees, which essentially ensures that most of the laser light is “caught.” From there the beam is transferred to the second telescope, the outgoing transmitter, which sends it to the target.[97] To achieve the same robustness as the space-based laser architecture for theater ballistic missile defense, twenty mission mirrors would be required.[98] The assumptions that were used to estimate the size and power of the laser and diameter and weight of the space-based mirrors are outlined in Table 8.

Table 8. Ground-Based Laser System Parameters[99]

System Parameters	Comments
Beam Director	8 meter primary
Relay Mirrors	4 mirrors in geosynchronous earth orbit, 20 meter diameter, 40,000 kilometers from ground laser
Mission Mirrors	20 mirrors in low earth orbit, 8 meter diameter for each telescope, 35,000 kilometers from relay mirrors and 4,000 kilometers from target
Laser Power Losses	25 percent due to all effects: atmospheric turbulence, absorption, and cumulative laser jitter
Ground Laser Output Power	25 megawatts based on ranges between laser and space mirrors and power loss values

In addition to the large primary mirrors, each mirror satellite also includes an active control system for the mirror surface, laser beam aberration reduction, and optics to focus the beam, as well as satellite “housekeeping” subsystems (power, communication, attitude control, and thermal control).[100] The use of lightweight mirror technology, similar to NASA's Next Generation Space Telescope (NGST), would keep the weight of the mirror quite low.[101] Based on this technology, the relay mirror spacecraft would weigh an estimated 34,000 kilograms, and the mission mirror satellites, with their dual telescope design, would weigh 8,500 kilograms. [102]

Architecture Evaluation

The ground laser and large space mirrors must overcome some significant obstacles that are not encountered with the space-based laser architecture. For instance, the greater distance between the lasers and the targets dramatically increases the laser power requirement. Also, atmospheric losses will be larger than the space-based laser system, which in turn not only increases the power requirement for the laser but also increases the demands on the adaptive optics for controlling the quality of the laser beam.[103] Furthermore, the large space mirrors must be built to high optical quality standards, but these will also be susceptible to damage from space debris and high-energy space particles.[104]

Technology Assessment. The technological challenges associated with the ground-based laser system primarily involve the optics (fabricating large mirrors, deploying large mirror systems in space, and applying optical coatings to mirrors) and achieving sufficient output power for the ground laser. Since the 1980s, the SDIO and the BMDO have studied large space mirrors, which was described earlier in the discussion of the Large Optics Demonstration Experiment and Large Advanced Mirror Program. Currently, NASA is investigating new concepts for the NGST, with a primary mirror for this telescope that is eight meters in diameter and can be either deployable or inflatable.[105] To reduce launch costs, NASA plans to keep the maximum weight to only 2,700 kilograms for the entire system (telescope and spacecraft) and launch it on an Atlas rocket.[106]

To achieve this demanding requirement, the telescope design incorporates low density, thin mirrors that are unfolded in space much like the opening of flower petals. Both TRW and the Harris Corporation have preliminary design concepts based on radio antenna applications. This large mirror will have its "figure," i.e. shape, corrected by a deformable mirror concept that was developed by the SDIO. NASA has implemented an aggressive risk reduction program to demonstrate these technologies.[107] Much of the NASA mirror technology is applicable to the ground-based laser's space mirrors, but because the ground-based laser relay mirrors require diameters of 20 meters, it significantly increases the technological difficulty. Even with the NASA technology, the relay mirror weight is far beyond the current capacity of launch vehicles, particularly if it is put in geosynchronous orbit. The implication of these constraints is that the United States would require a new launch vehicle that is even larger than that needed for the space-based laser architecture. Another alternative is a technological leap that significantly reduces the weight of the relay mirror.

In addition to the tremendous size of the mirrors, the mirror coatings for space and ground are unique to the ground-based laser problem because they must be capable of withstanding significant heat from the laser beam. Optical coatings on all the mirrors which "see" the high-energy laser must reflect over 99 percent of the beam or be capable of absorbing the remaining heat from the laser and remain intact. The high-energy laser programs such as MIRACL and Alpha have considerable experience with this type of high reflectivity coating. The conclusion of studies cited earlier was that the optical coating processes would meet the performance requirements of the ground-based laser system.[108]

It should be noted, however, that the power required for each ground-based laser is at least twenty-five times greater than that which has been demonstrated to date. To achieve this increase in power, multiple lasers must be optically coupled together to produce one powerful beam, and while this is physically possible, it will take years to overcome the engineering challenges.

Table 9. SBL, GBL Technological Feasibility Comparisons

Systems	SBL Feasibility	GBL Feasibility
High-Energy Laser	4 (no breakthroughs required)	2 (requires multiple breakthroughs)
Optical Components	4 (no breakthroughs required)	2 (requires multiple breakthroughs)
ATP/FC	4 (no breakthroughs required)	3 (major challenges remain)
Integration	3 (major challenges remain)	3 (major challenges remain)
Launch	3 (major challenges remain)	3 (major challenges remain)
Totals	18	13

The technological feasibility and maturity of the ground-based laser system falls short of the space-based laser system.[109] Placing twenty-meter diameter relay mirrors at geosynchronous earth orbit will require major technological breakthroughs to reduce the weight and volume sufficiently to allow the platforms to fit on an existing launch vehicle. While the COIL system is not as constrained by weight or volume as is the case with the space-based laser, it must be capable of much more power than has been demonstrated so far.

Table 10. SBL, GBL Technological Maturity Comparisons

Systems	SBL Maturity	GBL Maturity
High-Energy Laser	4 (less than five years to field)	2 (ten to fifteen years to field)
Optical Components	4 (less than five years to field)	2 (ten to fifteen years to field)
ATP/FC	4 (less than five years to field)	4 (less than five years to field)
Integration	2 (ten to fifteen years to field)	3 (five to ten years to field)
Launch	2 (ten to fifteen years to field)	2 (ten to fifteen years to field)
Totals	16	13

Cost Estimate. For this architecture to be a viable alternative to the space-based laser concept, the cost must be at least the same and preferably less than the space-based option. In order to compare architectures fairly, the cost estimates in this study for the ground-based laser architecture are divided into two components: the on-orbit segment and the ground segment. These estimates are based only on DOD's experience with previous space programs and high-energy laser systems.

Recently, NASA published a paper which suggested that the new telescope, with an aperture of eight meters, will cost only about twenty-five percent of the Hubble space telescope, which has an aperture of 2.4 meters. That study cites several ways to reduce program costs, including improvements in mirror fabrication facilities, computer processing, and streamlined bureaucracy. NASA's goal is for the entire program to cost $500 million including research, development, test, and launch.[110] Since some of the research and development efforts for the one-of-a-kind NGST may benefit the space mirror systems for this architecture, it is conceivable that the costs of ground-based laser system will be reduced. Despite this potential cost improvement, the space components will be estimated at $100,000 per kilogram if this is to be consistent with the space-based laser system estimates.

In the case of the space mirrors, the constellation's estimated weight is 306,000 kilograms (four relay mirror platforms at 34,000 kilograms each and twenty bifocal mirror platforms at 8,500 kilograms each). Based on the historical cost estimate of $100,000 per kilogram, the costs for the platforms should be $30.6 billion. Using the technological readiness level described in a previous section, the rating for the ground-based laser architecture means that the conceptual design has been formulated. This rating requires another twenty-five percent factor added on to the estimate for a total of $38.25 billion. When launch expenses are included, based on the Evolved Expendable Launch Vehicle's proposed costs of $5,650 per kilogram, the total space segment cost rises to $40 billion.*

In the case of the estimated cost for the ground portion of the ground-based laser architecture, there are strong arguments that this architecture will decrease on-orbit weight and therefore reduce the overall cost of the system. There are, however, problems with such analyses of the cost of the ground segment.

In the past, high-energy lasers were built for experimental purposes rather than for operational weapon systems. Estimating the cost of a laser system from an experimental system is inherently risky because it does not take into consideration the additional specifications that are required by operational systems. Unfortunately, the only “operational” system on which this estimate can be based is the Airborne Laser (ABL) program, which is currently

---

* The following methodology was used to calculate the cost estimate for the on-orbit segment of the GBL architecture:

1. GBL on-orbit development cost = GBL on-orbit weight x cost per kilogram
= 306,000 kg x $100,000/kg
= $30.6 x 10^9
2. Added cost for level of technological readiness =development cost x 25%
= ($30.6 x 10^9) x 0.25
= $7.65 x 10^9
3. Launch cost = GBL on-orbit weight x cost per kilogram to orbit

under development. As discussed earlier, this program also uses a Chemical Oxygen Iodine Laser device as its laser, but it is deployed on an aircraft. This is a significant difference because there is a requirement for an airborne system to be lower in weight, which reflects the fact that weight is constrained by the volume of the aircraft. Considering that the projected cost for each ABL aircraft is \$1 billion, the cost per watt of output power is \$330.[111] Using an optimistic estimate in which fifty percent of the cost was to fit the system within the aircraft (a constraint which is not required for a ground-based laser), the cost per watt is reduced to \$165. With this cost estimate, each ground laser site would cost roughly \$4.13 billion, and five sites would cost \$20.6 billion. This places the entire ground-based laser architecture, including space and ground segments, at \$61 billion.*

Another source for a cost comparison can be derived from an estimate of developing a ground-based laser anti-satellite system.[112] If we use a linear extrapolation of the laser power required for missile defense, each site would cost roughly \$26 billion, and therefore, five sites would cost roughly \$130 billion. Based on this number, the ground system plus the \$40 billion for the space segment would put the total system cost in the range of \$170 billion.* The large variation in cost estimates for the ground-based system makes it difficult to recommend this architecture as a more cost effective approach in comparison with the space-based laser approach.

Table 11. SBL, GBL Cost Comparisons

Cost Range	**SBL**	GBL
Low Estimate	\$17 billion[1]	\$61 billion [2]
High Estimate	\$81 billion [3]	\$170 billion [4]

Notes: 1) BMDO estimate, 2) Author's estimate based on "ABL" model, 3) Author's estimate, 4) Author's estimate based on the "ASAT" development model.

Clearly, the great technological challenges associated with achieving the laser output power as well as building and placing the twenty-meter diameter relay mirrors into geosynchronous orbit, reduces the attractiveness of the ground-based laser system.

= 306,000 kg x \$5650/kg
= \$1,729 x 10^9
4. Total on-orbit cost = development cost + added cost for technological readiness + launch cost
= (\$30.6 x 10^9) + (7.65 x 10^9) + (\$1.729 x 10^9)
= \$39.979 x 10^9 or about \$40 billion

---

* The following methodology was used to calculate the cost estimate for the total cost of GBL architecture using the "ABL" model
1. GBL ground segment cost/site = GBL power (in watts) x cost/watt
= 25 x 10^6 W x \$165/watt
= \$4.125 x 10^9
2. Cost for five sites = cost/site x number of sites
= (\$4.125 x 10^9) x 5
= \$220,625 x 10^9
3. Total cost = on-orbit segment cost + ground segment cost
= (\$39.979 x 10^9) + (\$20.625 x 10^9)
= \$60.631 x 10^9 or about \$61 billion

*** the following methodology was used to calculate the cost estimate for the total cost of GBL architecture using the "ASAT" model:
1. GBL cost/site = GBL brightness (in watts/steradian) x ASAT cost/watt/steradian
= 20 x 10^{18} W/steradian x (\$1.3 x 10^9/1 x 10^{18} W/steradian)
= \$26.0 x 10^9
2. Cost for five sites = Cost/site x number of sites
= (\$26.0 x 10^9) x 5
= \$130.0 x 10^9
3. Total cost = on-orbit segment cost + ground segment cost
= (\$39.979 x 10^9) + (\$130.0 x 10^9)
= \$169.979 x 10^9 or about \$170 billion

Technology Development Programs

Despite this assessment, a few promising technologies merit long-term investment. The two significant challenges facing this architecture are achieving the high power from the laser and reducing the cost of the ground laser. Revolutionary concepts for different laser options or optically coupling multiple lasers together need to be investigated for further development. Theoretically, multiple lasers could be optically coupled together and projected as one intense beam from the ground to the relay mirror. Other approaches include the use of adaptive optics to combine the beams from multiple apertures.[113] These techniques are still at their infancy and clearly require more laboratory analysis and demonstrations.

One of the more promising areas for technological investment is real-time holography to correct for wavefront errors in large mirrors. Currently, the surfaces of large mirrors are manufactured to stringent standards through grinding and polishing. The surface must maintain the same optical qualities during launch, deployment, and operation. Yet, when mirrors are constructed of thin, lightweight materials, the optical quality cannot be maintained except through complex mechanical systems. To alleviate this problem, Phillips Research Site is conducting research in a real-time holographic compensation system, which would allow the mirror to be far less than perfect by using an all-optical process to compensate for imperfections in the surface quality. The outcome of the research could have far reaching implications not only for a ground-based laser system, but also for reconnaissance, remote sensing, and astronomical satellites.[114]

Although NASA is aggressively pursuing large deployable mirror technology, active involvement by the Air Force with NASA could be extremely fruitful. Since the National Reconnaissance Office (NRO) is interested in large, deployable optical systems for imaging satellites, it may be interested in combining efforts and resources into the program. For a relatively small investment, the Air Force could integrate its research and development efforts in large mirrors with similar efforts underway at NASA.

VII. Space-Based Laser "Plus" Architecture

The most intriguing of these concepts is space-based laser weapons that are deployed in conjunction with large orbiting mirrors. This "space-based laser plus" (SBL Plus) option potentially could reduce the number of space-based laser platforms, reduce on-orbit weight, and overall costs, and do so while providing a more robust constellation. The concept behind this architecture is to decrease the number of platforms and insert bifocal mirrors into the same orbit as the laser weapons.

As with the first concept, placing the weapon in orbit takes advantage of the unique aspects of space. But unlike ground-based laser systems, the space-based laser is able to cover a large theater of operations directly, and is limited only by the platform's orbital altitude and the range to the missile. As the laser platform's altitude increases, the size of the area it sees increases, and the number of platforms that are required for global coverage decreases. Yet, the farther the laser weapon is from the missile, the more energy is required to destroy it, since the laser beam's spot size increases with the distance between the laser and the target. In addition, the platform's mechanical pumps and cooling systems create vibrations that cause the beam to jitter, and in turn, spread the laser's energy. To maintain the same intensity on a missile, a higher-altitude orbit would require a more powerful laser or a primary mirror with a larger aperture.

A more attractive alternative to compensate for this loss in intensity from a higher orbit and beam jitter is to fire the laser platform at space mirrors. This concept, which was explored briefly in the 1980s, combines the strengths of both previously described architectures to produce an effective and technologically achievable system at lower cost.[115]

Operational Concept

One of the more significant costs of the space-based laser-only architecture is the laser platform. If the number of these large platforms could be reduced and if the architecture could still maintain its operational effectiveness, then the overall cost would decrease. In the space-based laser "plus" architecture, mirrors are placed in orbit between the laser platforms and positioned so that they are always in view of a laser. These mirrors allow the laser platform to fire directly at the missile or relay the laser beam through the mirror depending on the location from which the missile is launched.

For example, if a missile is launched directly in the laser platform's field-of-view, then the laser fires directly at the missile. If, instead, the missile is fired in the mirror's field-of-view, then the laser platform closest to the mirror would direct the laser beam towards that mirror. The mirror would "catch" the laser beam, refocus, and direct it against the missile. This concept requires fewer laser platforms because the space-based mirrors provide the global coverage, while the laser's intensity remains sufficient because the mirrors attenuate the jitter and refocus the beam. One concept for these mirrors is the bifocal design discussed in the previous section. With this dual telescope design, one telescope would always be pointed in the direction of a laser platform, while the other telescope would be aimed at the earth's surface.[116]

The exact number of laser platforms, the size of the laser platforms and mission mirrors, and orbits for each system requires a detailed architecture analysis. One possible configuration consists of ten bifocal mission mirrors and ten space-based laser platforms. The space-based laser platforms would have a hydrogen fluoride laser with a power of eight megawatts and a primary mirror aperture of eight meters. The mission mirrors would consist of an eight-meter aperture for each telescope.

Architecture Evaluation

An analysis in the mid-1980s considered a large ICBM threat environment against two different space-based laser constellations. One constellation included space-based laser platforms only, while the other was a mix of space-based laser platforms and orbiting mirrors. The report concluded that the space-based laser with orbiting mirrors had several advantages: a lower overall weight of the payloads that must be placed in orbit, a reduced aperture, a less stringent constraint on laser beam jitter, and a reduction in the overall vulnerability of the system.[117] Although this study assumed the earlier-cited SDI-type missile scenario, the results for today's theater ballistic missile threat will be similar. In comparison with the previous two concepts, the technological requirements for this architecture are far less demanding.

Technology Assessment. One distinct advantage of this architecture is the possibility of reducing the weight and expense of the system. Instead of twenty laser platforms, the concept requires roughly ten platforms and ten orbiting mission mirrors. The combined weight of the space-based lasers and mission mirrors is approximately forty percent less than that of the space-based laser-only architecture. Lightweight mirror technology, which is being developed independently by NASA and the Air Force Phillips Research Site, would reduce the weight of the mission mirror and permit this technology to fit on existing launch vehicles. With this improved technology, the eight-meter bifocal mirror systems would weigh 8,500 kilograms each.[118]

Another benefit of the SBL "Plus" architecture is that it decreases the size of the space-based laser so that the system would not require the development of a new launch vehicle for placing these systems into orbit. The addition of space-based mirrors in the architecture creates a wide range of options for reducing the weight of the laser platforms. One approach is to make the laser platform's aperture smaller and increase the number of mission mirrors in orbit. This system maintains the same effectiveness because the range between the laser and the mirror is less and the mission mirrors refocus the laser beam while attenuating the jitter of the laser platform.

A particularly intriguing option is to build the laser platform without the large beam director. The laser device, with its chemical fuels, is positioned close enough to a mission mirror to perform the function of the beam expander. One drawback of this concept is that the laser cannot fire directly at a missile, but must always be fired at a space-based mirror before striking the target. Yet, the advantage is that the laser platform's weight is significantly less than the SBL-only design, and offers the benefit of fitting on an existing launch vehicle.

A third alternative is to reduce the output power of the laser and increase the transmitting aperture of the bifocal mirror. The larger aperture of the mission mirror compensates for the lower laser power, but provides the same laser intensity on the target. These three examples illustrate the increased flexibility that is derived from adding mission mirrors to the architecture. The broad observation is that any tradeoffs must balance the size and cost of laser platforms and mission mirrors with increasing the technological feasibility of the weapon system and allowing each platform to fit on an Evolved Expendable Launch Vehicle.

Table 12. SBL, GBL, and SBL "Plus" Technological Feasibility Comparisons

Systems	SBL Feasibility	GBL Feasibility	SBL Plus Feasibility
High-Energy Laser	4 (no breakthroughs required)	2 (requires multiple breakthroughs)	4 (no breakthroughs required)
Optical Components	4 (no breakthroughs required)	2 (requires multiple breakthroughs)	4 (no breakthroughs required)
ATP/FC	4 (no breakthroughs required)	3 (major challenges remain)	4 (no breakthroughs required)
Integration	3 (major challenges remain)	3 (major challenges remain)	3 (major challenges remain)
Launch	3 (major challenges remain)	3 (major challenges remain)	4 (no breakthroughs required)
Total	18	13	19

Note: This assessment assumes the development of a successful space-based laser readiness demonstrator and an overall reduction of the size of the space-based laser platform.

Table 13. SBL, GBL, and SBL "Plus" Technological Maturity Comparisons

Systems	SBL Maturity	GBL Maturity	SBL "Plus" Maturity
High-Energy Laser	4 (less than five years to field)	2 (ten to fifteen years to field)	4 (less than five years to field)
Optical Components	4 (less than five years to field)	2 (ten to fifteen years to field)	4 (less than five years to field)
ATP/FC	4 (less than five years to field)	4 (less than five years to field)	5 (possible today)
Integration	2 (ten to fifteen years to field)	3 (five to ten years to field)	4 (less than five years to field)
Launch	2 (ten to fifteen years to field)	2 (ten to fifteen years to field)	5 (possible today)
Total	16	13	22

Note: This assessment assumes the development of a successful space-based laser readiness demonstrator and an overall reduction of the size of the space-based laser platform.

The space-based laser "plus" architecture draws on components from both the space-based laser and the ground-based laser concepts. As with the space-based laser-only architecture, the SBL Readiness Demonstrator (SBLRD) is essential. This technical assessment is based on the assumption that the demonstrator is successfully funded, built, and tested. In addition, this architecture also relies on using the concept of bifocal mission mirrors. It consists of two connected telescopes that are coupled by smaller mirrors to transfer the beam from the receiving telescope to the transmitting telescope. The receiver telescope is pointed directly at the space-based laser platform so that it receives the laser beam directly into its primary mirror, transfers the beam to the second telescope, the outgoing transmitter, and then sends it to the missile.[119]

Cost Estimate. While the SBL "Plus" has technological benefits over both the space-based laser-only and ground-based laser concepts, a thorough study of this concept is required before a meaningful cost estimate is possible. However, the following analysis provides a rough estimate of the overall cost of this system in comparison with other architectures. The twenty platform space-based laser-only constellation will cost between $17 billion to $29 billion, based on the estimates by the DOD. But an analysis based on weight on-orbit yields the more realistic cost estimate of $81 billion. As described in the previous section, the ground-based laser architecture is estimated to cost as much as $170 billion.

The cost estimate for the SBL "Plus" architecture is based on the weight of the space platforms. Each of the space-based laser platforms weighs an estimated 35,000 kilograms. If each mission mirror were the same aperture size and weight as the bifocal mirrors for the ground-based laser architecture, they would each weigh 8,500 kilograms. For a space-based laser with orbiting mission mirrors, the number of laser platforms could be reduced by fifty percent from the space-based laser-only architecture. With ten mission mirrors placed in low earth orbit, the overall system weight would be 435,000 kilograms (ten laser platforms at 35,000 kilograms each and ten mission mirrors at 8,500 kilograms each). Using the historical cost of $100,000 per kilogram, the cost for the systems would be $43.5 billion.

Since the laser demonstrator will test the critical laser hardware in space but not the bifocal mirrors, the space-based laser "plus" architecture merits a technology readiness level of 5, which adds another ten percent to the estimate based on experience from previous space programs. When launch costs are included (based on the Evolved Expendable Launch Vehicle's proposed costs of $5,650 per kilogram), the total cost rises to $50 billion.*

---

* The following methodology was used to calculate the cost estimate for the SBL Plus architecture:
1. SBL Plus development cost = SBL Plus total weight x cost per kilogram
= 435,000 kg x $100,000/kg
= $\$43.5 \times 10^9$
2. Added cost for level of technological readiness = development cost x 10%
= ($\$43.5 \times 10^9 \times 0.10$
= $\$4.35 \times 10^9$
3. Launch cost = SBL Plus total weight x cost per kilogram to orbit

= 435,000 kg x \$5650/kg
= \$2,458 x 10^9
4. Total cost = development cost = added cost for technological readiness + launch cost
= (\$43.5 x 10^9) + (4.35 x 10^9) + (\$2.458 x 10^9)
= \$50.308 x 10^9 or about \$50 billion

These costs are about forty percent less than the cost of the space-based laser-only option and seventy percent less than the cost of the ground-based laser system.

Table 14. SBL, GBL, and SBL "Plus" Cost Comparisons

SBL	GBL	SBL "Plus"
\$81 billion	\$170 billion	\$50 billion

Technology Development Programs

For this concept, the appropriate programs for developing this technology are a combination of the previous two architectures. Clearly, the Readiness Demonstrator is essential because without an on-orbit test of a subscale system, numerous and challenging system engineering issues remain unresolved. Including a subscale bifocal mirror in space with the laser demonstrator program offers several unique opportunities. Furthermore, the research being conducted by the Phillips Research Site on holographic wavefront correction may allow large bifocal mirrors to have a less than perfect shape because it uses an all-optical process to compensate for imperfections in the surface of the mirror.

A combined Air Force, NASA, and NRO program that demonstrates the technology for bifocal mirrors could help share the cost, and build strong bureaucratic support for these programs. From past experiences, consolidating DOD and NASA programs is not always popular with DOD acquisition policy makers but can be cost effective if planned carefully.[120] The optimum demonstration would include a bifocal mirror that is launched into space concurrently with the laser demonstrator. If there was funding for building a bifocal mirror satellite and launching it at the same time as the launch of the demonstrator, then the on-orbit tests of the high-energy laser could be coordinated with the mirror. The Air Force could demonstrate the space-based laser with the orbiting mirrors architecture, NASA would be able to demonstrate a space-qualified deployable mirror for the NGST, and the NRO could use this "space-qualified" technology for future imaging satellites.

VIII. Conclusions

The main purpose of this study is to explain three alternative architectures for high-energy laser space systems. Lasers such as MIRACL and Alpha have demonstrated that the technology for achieving the necessary power levels for the lasers is within the reach of the U.S. defense establishment. Other programs, including the Large Optics Demonstration Experiment and the Large Advanced Mirror Program, validated the design and manufacturing concepts for large optical systems. Programs such as the Rapid Retargeting/Precision Pointing Simulator and Structure and Pointing Integrated Control Experiment confirmed the feasibility of technologies for controlling and stabilizing large space structures. Finally, the Space-Based Laser Readiness Demonstrator will bring the individually tested systems into an integrated package in order to demonstrate that the system works in space.

While the second alternative, the ground-based laser system architecture, is attractive in some aspects, it is far less mature and potentially far more expensive than the space-based laser concept. The ground-based high-energy laser is the most technically challenging and costly system to develop. The first reason is that this system must be capable of producing laser power up to twenty-five times greater than that which has been demonstrated to date. Although it is technologically feasible to develop this system, the costs are likely to be significantly greater than the space-based laser system. Furthermore, the 20-meter diameter relay mirrors for this concept push the envelope of technology significantly further than competing concepts, which increases the technical risk and cost of this laser system.

Table 15. Strengths and Weaknesses of Competing Architectures

System	**Space-Based Laser**	**Ground-Based Laser**	**Spaced-Based Laser "Plus"**
Strengths	Readiness Demo will address most major issues	Eliminates need to size laser to existing launch vehicle	Reduces total weight on-orbit and cost of system
Weaknesses	Requires two launches per laser platform or new launch vehicle	Laser and space-based mirror requirements drive system cost	Bifocal mirror technology has not been demonstrated

The principal recommendation of this study is that the Air Force, in conjunction with the Ballistic Missile Defense Organization, should give serious consideration to the SBL Plus option, which is a combination of space-based lasers with orbiting mirrors. When bifocal mirrors are positioned in orbit between the laser platforms, it will reduce the number of the heavy space-based lasers that must be put into space, and hence it will reduce the overall weight and cost of the weapon system. In this concept the space-based lasers would either fire directly at the missile or relay the laser energy to a mission mirror, and the bifocal mission mirrors would "catch" the laser beam from the laser platform, refocus, and direct it against the target. In addition to reducing the number of laser platforms, this configuration of mission mirrors would attenuate some of the laser jitter. In comparison with the space- and ground-based laser concepts, this is a far less technologically demanding approach, for several reasons.

The first is that size of the mission mirror is approximately the same as NASA's NGST, which is already under development. Second, the size of the primary mirror or the output power of the laser could be reduced from that envisioned in the original concept for the space-based laser. Finally, with a smaller laser platform, the system could fit on the proposed Evolved Expendable Launch Vehicle and therefore not require a new launch vehicle. If the SBL Plus architecture were selected, the best demonstration of its feasibility would be a jointly funded (AF, NASA, and NRO) bifocal space mirror that is conducted concurrently with the space-based laser demonstrator.

Recommendations. The Department of Defense should incorporate space mirrors into the space-based laser architecture and pursue a number of other steps.

First, it is necessary to conduct a detailed architecture study for a space-based laser system with mission mirrors. This study must examine the tradeoffs between laser power, laser jitter, aperture size, mission mirror size, orbits, weight, and total life-cycle cost.

Second, the Department of Defense, in conjunction with the Air Force, should fund a bifocal mirror program that could be launched before, or concurrently with, the Space-Based Laser Readiness Demonstrator. This effort should focus on the development of a sub-scale, rather than full-size, mirror, and address the key acquisition, tracking, and pointing issues. The BMDO and Air Force should encourage a combined program with NASA and the

NRO to test the mirror technology in space, and these organizations should invest along with NASA and the NRO in the mirror technology that is under development for the NGST.

Third, it is essential to investigate the ancillary missions that could be conducted with bifocal space mirrors, including high-resolution ground imaging, high-resolution space imaging, and remote sensing. It is equally important to continue the development of real-time holography at the Phillips Research Site as a way to improve the ability to correct the wavefront errors that will distort lasers and hence reduce their operational effectiveness.

In a time of declining defense budgets, American policy makers must select the laser weapon architecture that is the most technologically achievable and cost-effective. Despite the fact that ground-based lasers have some advantages, the optimum path for the United States at the beginning of the twenty-first century is to develop a space-based laser with orbiting mirrors as part of a long-range strategy for using high-energy laser weapons to enhance the capability of the United States to defend itself against ballistic missiles.

Glossary

ABL Airborne Laser
ABM Anti-Ballistic Missile
ALI Alpha/LAMP Integration
AO Adaptive Optics
ASAT Antisatellite
ATP/FC Acquisition, Tracking, Pointing, and Fire Control

BMD Ballistic Missile Defense
BMDO Ballistic Missile Defense Organization

COEA Cost and Operational Effectiveness Analysis
COIL Chemical Oxygen Iodine Laser
CW Continuous Wave

DARPA Defense Advanced Research Projects Agency
DEW Directed Energy Weapon
DF Deuterium Fluoride
DOD Department of Defense

EELV Evolved Expendable Launch Vehicle

GBL Ground-based Laser
GEO Geosynchronous Earth Orbit

HEL High-Energy Laser
HF Hydrogen Fluoride

ICBM Intercontinental Ballistic Missile
IRBM Intermediate Range Ballistic Missile

J joule (unit of energy)

LAMP Large Advanced Mirror Program
Laser Light Amplification through Stimulated Emission of Radiation
LEO Low Earth Orbit
LODE Large Optics Demonstration Program

MEO Medium Earth Orbit
MIRACL Mid-Infrared Advanced Chemical Laser
MRBM Medium Range Ballistic Missile
MTCR Missile Technology Control Regime
MW Megawatt (1,000,000 watts)

NGST Next Generation Space Telescope
NRO National Reconnaissance Office

SBL Space-based Laser
SBLRD Space-based Laser Readiness Demonstrator
SDI Strategic Defense Initiative
SDIO Strategic Defense Initiative Organization

SLBM Submarine Launched Ballistic Missile
SOR Starfire Optical Range, Kirtland AFB, NM
SRBM Short Range Ballistic Missile

TBM Theater Ballistic Missile
TMD Theater Missile Defense

USAF United States Air Force

Notes

1. These are not the only possible architectures for theater missile defense. Another architecture is using an Airborne Laser (ABL) system in conjunction with relay mirrors. Because the ABL operates above the clouds (and hence most of the atmospheric turbulence), performance reductions from weather and atmospheric turbulence are reduced. While another option is a broader mix of forces that includes Space-based Lasers (SBL), Ground-based Lasers (GBL), ABL, and relay mirrors, these concepts are beyond the scope of this paper.

2. Frank L. Pedrotti, S.J. and Leno S. Pedrotti, *Introduction to Optics*, 2nd edition, (Upper Saddle River, NJ: Prentice Hall, 1993), 484, 497.

3. Major Michael J. Muolo, *Space Handbook*, vol. 2, Air University Report AU-18, (Maxwell AFB, AL: Air University Press, December 1993), 229.

4. Vincent T. Kiernan, "The Laser-Weapon Race is On," *Laser Focus World*, December 1996.

5. William J. Broad, "From Fantasy to Fact: Space-based Laser Nearly Ready to Fly," *New York Times*, Sunday, 6 December 1994, sec. C.

6. Suzann Chapman, "The Airborne Laser," Air Force Magazine, January 1996, 54-55.

7. *Air Force Issues Book 1997*, (Washington, DC: Department of the Air Force) 72-73. See also, Kenneth A. Barker, *Airborne and Spaceborne Lasers: Assessing the Compatibility of Technological and Operational Strategies,* Occasional Paper , Center for Strategy and Technology (Maxwell AFB, AL: Air War College, forthcoming).

8. Joseph C. Anselmo, "New Funding Spurs Space Laser Efforts," *Aviation Week and Space Technology,* 14 October 1996, 67.

9. Vincent T. Kiernan, "What is the Future of Space-Based Laser Weapons?" *Laser Focus World*, June 1997, 75.

10. Several studies such as *New World Vistas, Spacecast 2020,* and *Air Force 2025* have recommended space-based high-energy laser programs: USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Summary Volume (Washington, DC: Department of the Air Force, September 1996), 46-48. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Space Technology Volume (Washington, DC: Department of the Air Force, September 1996), xi-xii, 61-62. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Directed Energy Volume (Washington, DC: Department of the Air Force, September 1996), 22-26. *Spacecast 2020,* "Force Application" (Maxwell AFB, AL: Air University Press, June 1994) O-18. Lt Col Jamie G. Varni, et al., "Space Operations: Through the Looking Glass (Global Area Strike System)," Air Force 2025, Vol. 3, 92, CD-ROM, May 1996.

11. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Directed Energy Volume. (Washington, DC: USAF Scientific Advisory Board, September 1996), 22.

12. These criteria were derived from a study conducted by Mark Rogers, *Lasers in Space: Technological Options for Enhancing US Military Capabilities,* Occasional Paper No. 2, Center for Strategy and Technology (Maxwell AFB, AL: Air War College, 1997), 27-28.

13. David A. Bearden, Richard Boudreault, and James R. Wertz, "Cost Modeling," in *Reducing Space Mission Cost,* ed. James R. Wertz and Wiley J. Larson (Torrance, CA: Microcosm Press, 1996), 254.

14. *Ibid.*

15. *Ibid.*, 258. The author is aware of efforts to reduce the cost of military satellites through acquisition streamlining and the use of commercial practices. Since the cost estimates are used as a relative comparison only, these techniques will not be included.

16. *Ibid.*, 259.

17. Lt Col John R. London, III, *LEO on the Cheap,* Research Report No. AU-ARI-93-8 (Maxwell AFB, AL: Air University Press, 1994), 14.

18. *Ibid.*, 7-8.

19. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Space Applications Volume, (Washington, DC: USAF Scientific Advisory Board, December 1995), 89.

20. "Evolved Expendable Launch Vehicle," n.p.; on-line, Internet, 8 November 1997, available from http://www.laafb.af.mil/SMC/MV/eelvhome.htm.

21. Robert Wong, "Cost Modeling," in *Space Mission Analysis and Design,* ed. James R. Wertz and Wiley J. Larson (Torrance, CA: Microcosm Press, 1992), 718. Also, the Secretary of the Air Force/AQ has a homepage for space system cost models called "Space Boosters," n.p.; on-line, Internet, 10 November 1997, available from http://www.saffm.hq.af.mil/SAFFM/afcaa/space/space.html.

22. Leonard Spector, "Proliferation in the Third World," in *Security Strategy and Missile Defense,* ed. Robert L. Pfaltzgraff, Jr., (Hollis, NH: Puritan Press, 1995), 13.

23. “Ballistic Missiles Within Easy Reach for Many Nations,” *Washington Post,* 23 September 1997.
24. Spector, 13.
25. “The Threat is Real and Growing,” Centre for Defence and International Security Studies, n.p.; on-line, Internet, 25 October 1997, available from
http://www.cdiss.org:80/hometemp.htm.
26. *Ibid.*
27. Steven Erlanger, “U.S. Telling Russia to Bar Aide to Iran By Arms Experts,” *New York Times*, 22 August 1997, A1. Also, “Russia-Israel Strain Over Iran Missile Aid,” *New York Times*, 25 August 1997, A3.
28. “National Briefings: North Korea,” Centre for Defence and International Security Studies, n.p.; on-line, Internet, 28 October 1997, available from
http://www.cdiss.org/nkorea_b.htm.
29. William Van Cleave, “The Role of Active Defense,” in *Security Strategy and Missile Defense,* ed. Robert L. Pfaltzgraff, Jr., (Hollis, NH: Puritan Press, 1995), 101.
30. Spector, 16-17.
31. *Ibid.*
32. *Ibid.*, 13-14.
33. “The Threat is Real and Growing.”
34. “Missile Capabilities by Country,” Centre for Defence and International Security Studies, n.p.; on-line. Internet, 28 October 1997, available from
http://www.cdiss.org/table1.htm.
35. *Ibid*.
36. “Theater Missile Defense Programs,” Ballistic Missile Defense Organization, n.p.; on-line. Internet, 1 February 1998, available from
http://www.acq.osd.mil/bmdo/bmdolink/html/tmd.html.
37. “Space-based Laser Fact Sheet,” Ballistic Missile Defense Organization home page, n.p.; on-line, Internet. 28 October 1997, available from
http://www.acq.osd.mil/bmdo/bmdolink/html/bmdolink.html.
38. Major General Bengt Anderberg and Myron Wolbarsht, *Laser Weapons: The Dawn of a New Military Age* (New York: Plenum Press, 1992), 114.
39. Kosta Tsipis, “Laser Weapons,” *Scientific American,* December 1981, 55.
40. Geoffrey E. Forden, “The Airborne Laser,” *IEEE Spectrum*, September 1997, 46.
41. Muolo, 286-287.
42. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Directed Energy Volume (Washington, DC: Department of the Air Force, September 1996), 24.
43. Forden, 47.
44. *Ibid.*
45. Pedrotti, 427.
46. *Ibid.*, 484, 497.
47. Crockett L. Grabbe, “Physics of a ballistic missile defense: The chemical laser boost-phase defense,” *American Journal of Physics*, 56(1), January 1988, 32.
48. “Space-based Laser Fact Sheet.”
49. “Science and Technology of Directed Energy Weapons,” American Physical Society Study, *Reviews of Modern Physics,* vol. 59, Part II, July 1987, 58.
50. US General Accounting Office Report, “Ballistic Missile Defense - Information on Directed Energy Programs for FY 1985 Through 1993,” GAO/NSIAD-93-182, (Washington, DC: Government Printing Office, June 1993), 20.
51. Joseph C. Anselmo, “New Funding Spurs Space Laser Efforts,” *Aviation Week and Space Technology*, 14 October 1996, 67.
52. Forden, 42.
53. “Science and Technology of Directed Energy Weapons,” 60.
54. “Mid-Infrared Advanced Chemical Laser,” White Sands Missile Range home page, n.p.; on-line, Internet. 28 October 1997, available from
http://wsmr-helstf-www.army.mil/miracl.html.
55. Forden, 45.
56. Ibid., 42.

57. R. Benedict, et al., *Final Report of the Laser Mission Study.* PL-TR-93-1044, (Kirtland AFB, NM: Phillips Laboratory, July 1994), 15-16.
58. Forden, 45.
59. Benedict, 17.
60. An equally important use of adaptive optics, particularly for SBLs, is in compensating for wavefront errors that are internal to the laser system. This wavefront error is often due to less-than perfect beam quality from the laser device, but also can include error from the distortion caused by optical components and beam-path conditioning (for reference, this involves mechanisms for reducing beam distortion). In the case of the Airborne Laser, two adaptive optics systems are used, one for correcting internal wavefront error and the other for correcting distortions due to atmospheric turbulence.
61. John W. Hardy, "Adaptive Optics," *Scientific American,* June 1994, 60-65.
62. *Ibid.*
63. "3.5-Meter Telescope Fact Sheet," Phillips Laboratory Public Affairs home page, n.p.; on-line, Internet, 28 October 1997, available from http://www.plk.af.mil/ORG_CHART/DS/PA/FACTSHEETS/metertel.html. Also, author interviews at the Phillips Research Site.
64. Benedict, 19.
65. Schafer Corporation, "Space-based Laser: Pioneering Tomorrow's Defense," CD-ROM, 1997.
66. US General Accounting Office Report, 21.
67. "Space-Based Laser Fact Sheet."
68. US General Accounting Office Report, 35.
69. *Ibid.,* 36-37.
70. Another important test was the High Altitude Balloon Experiment (HABE) that was funded by the Ballistic Missile Defense Organization.
71. US General Accounting Office Report, 36-37.
72. *Ibid.,* 38.
73. Schafer Corporation.
74. The original notions for the Alpha laser, LODE optics and Talon Gold ATP/FC were technology development programs that were conducted in the early 2980's for an antisatellite SBL concept.
75. "Science and Technology of Directed Energy Weapons," American Physical Society Study, *Reviews of Modern Physics*, vol. 59, Part II, July 1987, 55.
76. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Directed Energy Volume. (Washington, DC: USAF Scientific Advisory Board, September 1996), 22.
77. Schafer Corporation, "Space-based Laser: Pioneering Tomorrow's Defense," CD-ROM, 1997.
78. *Ibid.*
79. USAF Scientific Advisory Board, 24.
80. Schafer Corporation.
81. *Ibid.*
82. USAF Scientific Advisory Board, 23.
83. Schafer Corporation.
84. Ibid.
85. London, 14. Also, "Evolved Expendable Launch Vehicle," n.p.; on-line, Internet, 8 November 1997, available from http://www.laafb.af.mil/SMC/MV/eelvhome.htm.
86. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Space Applications Volume. (Washington, DC: USAF Scientific Advisory Board, September 1996), 88-89.
87. Dr. Marc Hallada and Dr. Dustin Johnston, Schafer Corporation, author interview, 1 November 1997.
88. USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century,* Directed Energy Volume. (Washington, DC: USAF Scientific Advisory Board, September 1996), 25.
89. *Ibid.*
90. *Ibid.,* 24.
91. Numerous architecture studies have been performed for a ground-based laser system, the most recent and definitive of which was conducted in 1990. Two very detailed discussions are in: Lockheed Missile and Space Company, "Ground-based Laser Concept Formulation and Technology Development Planning" (U), Report Number: LMSC-L081927, 15 May 1990, (Secret) and TRW, "Ground-based Laser Concept Formulation and Technology Development Planning" (U), Report Number: 54579-6007-SX-00, 17 May 1990. A more general

discussion of the physics of the system is provided in “Science and Technology of Directed Energy Weapons,” American Physical Society Study, *Reviews of Modern Physics*, vol. 59, Part II, July 1987.
92. “Science and Technology of Directed Energy Weapons,” 210.
93. R.D. Stark, RF - *Laser Comparison and Considerations*, Aerospace Corporation Report ATR-94 (6486)-8 (El Segundo, CA: Aerospace Corporation, July 1993), 52-53. Also see Peter B. Ulrich and R. James Morgan, *SDIO Ground-based Laser Support - Laser and Power Technology, Volume VIB, Special Tasks in Ground-Based Laser Beam Control*, DNA-TR-90-103-V6B (Alexandria, VA: Defense Nuclear Agency) June 1991, B-45.
94. V. Krabbendam and T. Sebring, *Ground-based Laser System Optical Component Producibility Study - Executive Summary,* RADC-TR-90-355 (Griffiss AFB, NY: Rome Air Development Center, 1990), 3.
95. Relay mirror systems are also very interesting for a number of missions other than missile defense, including remote sensing, target designation, global wind measurements, and active imaging.
96. Dr. Marc Hallada and Dr. Dustin Johnston, Schafer Corporation, author interview, 1 November 1997.
97. Phillips Laboratory, Kirtland AFB, NM, author interview, 31 October 1997.
98. Estimate based on 2,000 km altitude and 4,000 km range from mission mirror to target. Verified by U.S. Air Force Academy Department of Physics, interviewed 26 November 1997. Also, another option for this architecture is to use all bifocal mirrors at LEO and count on multiple relay bounces to reach the target.
99. Estimates were derived by author and confirmed with Phillips Laboratory, Kirtland AFB, NM on 1 December 1997. If the ground telescope has an 8-meter diameter and a tracking/pointing accuracy of 100 nrad, the jittered spot diameter of the beam at 40,000 km is just under 20 meters.
100. Krabbendam and Sebring, 3.
101. The Next Generation Space Telescope (NGST) is intended to be a deployable optical system that offers the potential for lighter weight and easier packaging on a launch vehicle. This technology also may reduce the weight and volume of the SBL.
102. The mirror weight estimates for deployable mirrors vary greatly. One estimate provided by Phillips Laboratory, Kirtland AFB, NM is the mirror weight scales with $D^{1.3}$, where D is the mirror diameter. Another estimate is mirror weight scales with $D^{2.3}$ to $D^{2.7}$. This information was from Richard Dyer, Schafer Corporation, who was on NASA's NGST independent review team. To be conservative, this study used $D^{2.7}$ as the scale factor, included the mirror supporting mass in addition to the mirror, and added 2,000 kg for the spacecraft. The bifocal included another 20% to account for the transfer optics. Using the NGST weight of 2,700 kg:
For Relay Mirror:
(Mass of mirror / 2700 kg) = $(20\text{ m} / 8\text{ m})^{2.7}$; Mass of mirror = 32,000 kg
+ 2,000 kg (for spacecraft)
= 34,000 kg
For Mission Mirror:
(Mass of mirror / 2700 kg) = $(8\text{ m} / 8\text{ m})^{2.7}$; Mass of mirror = 2,700 kg
2,700 x 2 = 5,400 kg (for two mirrors with bifocal design)
+ 20% of 5,400 (for transfer optics)
+ 2,000 kg (for spacecraft)
=8,500 kg
103. Ulrich and Morgan, C-105.
104. “Science and Technology of Directed Energy Weapons,” 8.
105. Ron Cowen, “After Hubble: The Next Generation,” *Science News*, 26 April 1997, 262.
106. NASA, “NGST Costs,” 1 May 1997, n.p.; on-line, Internet, 5 November 1997, available from http://ngst.gsfc.nasa.gov/project/text/Execsum.html. For the detailed study report: H.S. Stockman, ed., “The Next Generation Space Telescope - Visiting a Time When Galaxies Were Young,” June 1997, on-line, Internet, 14 November 1997, available from http://oposite.stsci.edu/ngst/initial-study/.
107. Stockman, ed.
108. Robert R Kappesser, et al., *SDIO Ground—based Laser Support - Laser and Power Technology, Volume I - Optics,* DNA-TR-90-103-V1 (Alexandria, VA: Defense Nuclear Agency, May 1991), 4. Also, V. Krabbendam and T. Sebring, *Ground-based Laser System Optical Component Producibility Study - Executive Summary,* RADC-TR-90-355 (Griffiss AFB, NY: Rome Air Development Center, 1990), 4.
109. This assessment would be closer to the SBL architecture if the development programs involving deployable optics come to fruition. If large mirrors could be deployed in space from existing launch vehicles, the rating for this concept would likely improve.

110. NASA, “NGST Costs,” 1 May 1997, n.p.; on-line, Internet, 5 November 1997, available from http://ngst.gsfc.nasa.gov/project/text/Execsum.html.
111. Forden, 47. Dr. Forden states that each aircraft costs about $1 B and estimates the output power to be 3 MW.
112. Phillips Laboratory, Kirtland AFB, NM, author interview 1 December 1997. The estimate was based on a GBL ASAT system with a brightness of 1.0 x 10^{18} watts/steradian. This estimate included COIL design, fabrication, assembly, and check-out; beam control design, fabrication, assembly, and check-out; atmospheric compensation design, fabrication, assembly, and check-out; facility design, construction; system integration; system development testing; and operational testing. The total cost was $1.3 B over seven years. This extrapolation, which is based on a worst-case analysis, assumes a brightness factor approximately 20 times greater and therefore a cost 20 times higher.
113. “Science and Technology of Directed Energy Weapons,” 7.
114. Christopher M. Clayton, “Lethal/Sublethal DEW (Large Lightweight Optics Wavefront Compensation) - Real-Time Holography for Lightweight Space Optics,” *Laboratory Research Initiative Request, Executive Summary,* (Kirtland AFB, NM: Phillips Laboratory, 1997).
115. Lawrence Sher and Capt Stephan McNamara, “Relay Mirrors for Space Based Lasers,” Research Report, *Laser Digest*, AFWL-TR-88-68, Volume VI (Kirtland AFB, NM: Air Force Weapons Lab, May 1989).
116. Phillips Laboratory, Kirtland AFB, NM, author interview, 31 October 1997.
117. Sher and McNamara. A more detailed analysis of the physics is provided in Lawrence Sher,“Optical Concepts for Space Relay Mirrors,” Research Report, *Laser Digest*, AFWL-TR-88-68, Volume II. (Kirtland AFB, NM: Air Force Weapons Lab, May 1989).
118. Again, the following approach is used to calculate the weight of the mission mirror;
(Mass of mirror / 2700 kg) = $(8 \text{ m} / 8 \text{ m})^{2.7}$; Mass of mirror = 2,700 kg
2,700 x 2 = 5,400 kg (for two mirrors with bifocal design)
+ 20% of 5,400 (for transfer optics)
+ 2,000 kg (for spacecraft)
=8,500 kg
119. Phillips Laboratory, Kirtland AFB, NM, author interview, 31 October 1997.
120. Wiley J. Larson, “Process Changes to Reduce Cost,” in *Reducing Space Mission Cost,* ed. James R. Wertz and Wiley J. Larson (Torrance, CA: Microcosm Press, 1996), 22.

Center for Strategy and Technology

The Center for Strategy and Technology was established at the Air War College in 1996. Its purpose is to engage in long-term strategic thinking about technology and its implications for U.S. national security.

The Center focuses on education, research, and publications that support the integration of technology into national strategy and policy. Its charter is to support faculty and student research, publish research through books, articles, and occasional papers, fund a regular program of guest speakers, host conferences and symposia on these issues, and engage in collaborative research with U.S. and international academic institutions. As an outside funded activity, the Center enjoys the support of institutions in the strategic, scientific, and technological worlds. Principal funding is provided by the Air Force Research Laboratory (AFRL), with additional support from the Defense Advanced Research Projects Agency (DARPA).

An essential part of this program is to establish relationships with organizations in the Air Force as well as other Defense of Department agencies, and identify potential topics for research projects. Research conducted under the auspices of the Center is published as Occasional Papers and disseminated to senior military and political officials, think tanks, educational institutions, and other interested parties. Through these publications, the Center hopes to promote the integration of technology and strategy in support of U.S. national security objectives.

For further information on the Center on Strategy and Technology, please contact:

William C. Martel, Director
Air War College
325 Chennault Circle
Maxwell AFB
Montgomery, AL 36112

(334) 953-2384 (DSN 493-2384)

Email: wmartel@max1.au.af.mil

Titles in the Occasional Papers Series

1
Reachback Operations for Air Campaign Planning and Execution
Scott M. Britten, September 1997
2
Lasers in Space: Technological Options for Enhancing US Military Capabilities
Mark E. Rogers, November 1997
3
Non-Lethal Technologies: Implications for Military Strategy
Joseph Siniscalchi, March 1998
4
Perils of Reasoning by Historical Analogy: Munich, Vietnam, and the American Use of Force Since 1945
Jeffrey Record, March 1998

The Occasional Papers
series was established by the
Center for Strategy and Technology
as a forum for research
on topics that reflect
long-term strategic thinking
about technology and its
implications for
U. S. national security.

Center for Strategy and Technology
Air War College

Maxwell Air Force Base
Montgomery, Al 36112