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LASER WEAPONS IN SPACE:

A CRITICAL ASSESSMENT

by

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Contents

Illustrations

Page

Tables

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Abstract

Is the DOD pursuing the correct investment strategy for space-based high-energy lasers? 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. 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. Since the current Airborne Laser program utilizes only airborne assets, it is not part of this study. Three space-based architectures are evaluated against the 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 evaluation criteria include the technology risks and the estimated development and deployment costs. Also, technology development programs are described for each of the architectures to address the high-risk areas.

The results of this study suggest that the most technically sound and cost efficient architecture is *space-based lasers with orbiting mirrors* because this approach reduces the total weight and therefore cost on-orbit as well as the overall technical risks.

Chapter 1

Introduction

The Air Force, 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 the defense budget continues to decline. Selecting this investment strategy presents a challenge for policy makers due to competing technical, fiscal, and political factors. The Air Force is considering two high-energy laser architectures using space systems: space-based lasers and ground-based lasers with orbiting relay mirrors. Another potential option consists of a hybrid system using space-based lasers with orbiting mirrors. An independent assessment of the current laser and optics technology and an evaluation of the competing architectures will provide insight into which investment strategy to pursue. In this constrained budget era, the choice must be purposeful and based on the best information available.

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, in jest, to be “a solution without a problem.” 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, and laser radar-based navigational aids.[1] Laser guided munitions employed in Desert Storm brought new meaning to the idea of "precision engagement," and is just one example of where today the laser is seen as "a solution."[2] In fact, numerous countries are now developing their own laser technologies for weapons applications.[3] Since the early 1990s, lasers have demonstrated the capability to produce sufficient energy to be seriously considered, even by the most ardent skeptics, as potential weapons against the ballistic missile threat.[4] The vision is rapidly catching up with the technology where new, better, and smarter uses of lasers are envisioned.

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.[5] The USAF believes in and is already committed to such a weapon as the ABL as the weapon of choice to destroy theater ballistic missiles. This may be the first stepping stone towards building a space-based laser weapon system.[6]

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 B, is a subscale version of a proposed space-based laser weapon system for theater ballistic missile defense.[7] Congress continues to debate not only the usefulness of this concept but also the Antiballistic Missile (ABM) treaty implications. Some lawmakers actually believe that the laser weapon provides such a valuable defense that it is worth abrogating the treaty.[8]

The underlying assumption with this concept is that the entire weapon platform must be in space and that this is the most technically feasible and cost effective approach. But several other options are conceptually possible. One alternative architecture approach 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 route worthy of consideration entails using a combination of space-based lasers and optical relay mirrors in order to reduce the number of costly laser platforms.

There are a number of tough questions that 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 beam from the ground or from a smaller number of space-based lasers to the target? Are there insurmountable technical problems with any of these approaches? If the approach is feasible, are there any remaining technical shortfalls and what is the most effective way of overcoming them?[9]

This paper provides an independent assessment of the competing system architectures, which utilize space-based assets for missile defense. The foundation of the analysis is three evaluation criteria - technical feasibility, technical maturity, and relative cost. Also important to the analysis are 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 it, 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 technical complexities that must be confronted.

The evaluation of the system architectures examines three alternatives for high-energy laser weapon concepts, which utilize space assets: space-based laser system, ground-based laser with orbiting mirrors, and a combination of space lasers and orbiting mirrors. Based on the current missile threat and how much energy is required to destroy the missile, it considers the requirements for each weapon constellation. Following each overview of these architectures, the requisite technology will be examined and technology development programs will be presented. The cost for the architecture will be analyzed by applying a cost model that reflects earlier experiences with previous space mission programs. This approach enables a relative cost comparison of the different architectures.

The purpose of this study is to establish a framework for Air Force policy makers to help them make prudent decisions about the proper direction for funding technology development programs. The question is not "is a high-energy laser the correct choice," but 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.

Notes

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

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

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

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

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[5] Suzann Chapman, "The Airborne Laser," *Air Force Magazine*, January 1996, 54-55.

[6] *Air Force Issues Book 1997*, (Washington, D. C.: Department of the Air Force) 72-73.

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

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

[9] 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, D.C.: 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, D.C.: 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, D.C.: Department of the Air Force, September 1996), 22-26. *Spacecast 2020*, "Force Application" (Maxwell AFB, Ala.: Air University Press, June 1994) O-18. Lt Col Jamie G .G. Varni, et al., "Space Operations: Through the Looking Glass (Global Area Strike System)," *Air Force 2025*, Vol. 3, 92, CD-ROM, May 1996.

Chapter 2

Evaluation Approach

Laser weapon architecture studies conducted in the 1980s focused on defense from a massive Soviet ICBM attack, but obviously this threat has significantly changed.[1] Since then, the scenario for laser weapon employment has changed from strategic defense to a theater or national missile defense. Now the architectures concentrate on defending the US and our allies against ballistic missiles carrying weapons of mass destruction from rogue states and terrorist groups that are developing missile technology in addition to nuclear, chemical, and biological weapons. Given this change, the time is ripe for a new look at the options.

Technology Evaluation Criteria

This analysis will use a five-point scoring system, similar to the method applied today in government source selections, to evaluate the technical aspects of three space-based laser weapon architectures.[2] Although they are qualitative, the numerical scores allow a relatively straightforward method of comparing the strengths and weakness of each concept.

One measurement looks at the technical feasibility of a concept. Does this technology concept violate the laws of physics? Does it require a significant breakthrough or is it within reach of today's technology?

Table 1. Technology Feasibility Evaluation Criteria

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

The other factor in the evaluation is technical maturity. If the technology is achievable, then 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 improvement required, environment limitations, i.e. must the technology be tested in a zero gravity environment.

Table 2. Technical 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

Cost continues to be a key factor in space programs today and strongly influences whether a program will be funded. Numerous studies have examined past space programs and attempted to understand the factors that influence the cost of the program. Of all the factors, three stand out as potentially the most influential: payload type, weight and technical readiness.[3] The costs of satellites with similar purposes tend to be related to their total weight. The table below provides a basis for a range for a variety of space systems.

Table 3. Range of Costs for Space Systems[4]

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 evaluation criteria tables accounted for technology feasibility and maturity. A cost estimate for a high technology space program must also consider special factors that relate to technological readiness. One significant cost driver that past high technology programs have experienced is that technology risks increase program costs. How much the costs increase depends upon how far the technology has been demonstrated and tested in a space environment.[5]

Table 4. Technology Readiness Levels[6]

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. Launch costs, especially in the space laser architecture, may be a significant factor. The cost of transporting a satellite into low earth orbit ranges from $9.4 thousand to $32.4 thousand per kilogram.[7] The Space Shuttle and Titan IV are in the class of launch vehicles required for space-based laser platforms. Their cost for low earth orbit payloads is $11.3 thousand and $18.4 thousand per kilogram, respectively.[8] The typical costs for geosynchronous earth orbits are $14 thousand to $30.8 thousand per kilogram,[9] but these costs may come down by as much as 50 percent with the Air Force's proposed Evolved Expendable Launch Vehicle.[10]

Higher fidelity cost models for space systems are available, though they are beyond the scope of this paper.[11] The crucial aspect of this discussion is the relative cost comparison of the three architectures. For this purpose, cost comparisons will be based solely on weight, technical readiness, and launch costs.

Before examining the different laser systems, the ballistic missile threat must be analyzed and the missile vulnerabilities understood in order to effectively evaluate the architecture alternatives.

Notes

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

[2] Criteria derived from LtCol Mark Rogers, "Lasers in Space," Research Report (Maxwell AFB, Ala.: Air War College, 1997), 27-28.

[3] 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.

[4] Ibid.

[5] Ibid., 258. The author is aware of efforts to reduce the cost of military satellites such as acquisition streamlining and using ore commercial practices. Since the cost estimates are used as a relative comparison only, these techniques will not be included.

[6] Ibid., 259.

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

[8] Ibid., 7-8.

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

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

[11] 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.

Chapter 3

Ballistic Missile Vulnerabilities

Desert Storm highlighted the significant threat posed by ballistic missiles, particularly to our allies and perhaps one day to the United States. As witnessed in the war, even though Iraqi missiles were inaccurate and conventionally armed, they created a significant menace with powerful political effects but little military usefulness.[1] Today, the danger of a ballistic missile carrying a weapon of mass destruction is significant with the number of rogue states developing missile technology in addition to nuclear, chemical, and biological weapons. As a science advisor to former President Reagan testified 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."[2] 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 of terrorizing for rogue countries. These countries witnessed the effect that the Iraqi ballistic missiles had on the coalition forces during Desert Storm, particularly in almost 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, there were no defenses.[3] Some 36 countries have been identified as possessing ballistic missiles of some type, and 14 nations have the capability to build them.[4] These missiles, which range in size from large ICBMs to small Scud missiles, are dispersed worldwide.

The world's major powers hold the most advanced missiles. While Russia and China both possess intercontinental ballistic missiles (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 which could be modified for use as an ICBM.[5] The concern is that these countries, specifically Russia, may be helping other nations, who do not have the technology for building ICBMs, develop new ballistic missiles.[6]

There is increasing concern with ballistic missiles. The short range ballistic missiles (SRBMs) and medium range ballistic missiles (MRBMs) are proliferating rapidly and are the cause of the most concern. North Korea's Scud Bs and Scud Cs, both short range, could easily hit cities in South Korea. North Korea is also developing the Taep'o-dong II missile with a range estimated between 7500 kilometers and 10,000 kilometers. With its range of 7500 kilometers, the Taep'o-dong II could reach Alaska or Hawaii. If the longer-range estimate is correct, it could cover the western United States.[7] Some experts predict the missile may be operational by the year 2000.[8]

Missile technology appears to be a profitable export item for several nations. A number of countries are willing to export complete systems, technologies, or developmental expertise given the income that is generated by foreign sales. China, North Korea, and industrialized states in Europe are supplying ballistic missiles and missile-related technologies, which further increases the number of nations with ballistic missile capability.[9] Iran possesses submarine launched cruise missiles (SLCMs) by purchasing Kilo class submarines from Russia. The United Nations has attempted to curtail the sale of missile technology through the Missile Technology Control Regime (MTCR).[10]

The addition of weapons of mass destruction to a missile's warhead radically improves the rogue state's threat. Ballistic missiles coupled with nuclear, chemical, or biological warheads could provide a relatively economical tool for conducting asymmetric warfare. Following Desert Storm, rogue states realized the political impact of ballistic missiles, especially since they are becoming readily available and combining them with weapons of mass destruction add a new dimension where even the U.S. must take note.[11] India, Pakistan, and several Mid-East countries have refused to sign the Nuclear Nonproliferation Treaty (NPT) and may be 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.[12] Many countries have offensive chemical weapons programs; the most aggressive of which are Iran, Libya, and Syria, all of whom refused to sign the Chemical Weapons Convention or CWC.[13] A partial summary of the extent of proliferation is shown in the table below.

Table 5. Ballistic Missile Capabilities by Country[14]

	SRBM	MRBM	IRBM	ICBM	Cruise Missile	Nuclear	BW	CW	NPT	CWC	MCTR
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	

The Army's Patriot system used during Desert Storm demonstrated the political and military value of a ballistic missile defense. The Ballistic Missile Defense Organization is developing a family of missile defense systems to defeat a ballistic missile attack. Because of the diversity of the missiles described, they realize that a single system cannot accomplish the entire mission. With a family of systems approach they are 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.[15] A high-energy laser is a potential weapon for the upper-tier defense.

Ballistic Missile Vulnerabilities from Lasers

The Air Force considers high-energy laser weapons to be the best response to this increasing ballistic missile threat. Unlike the larger intercontinental ballistic missiles, small ballistic missiles are constructed with lighter weight materials and thinner outer skin, making them more vulnerable to laser weapons. A laser beam, however, could be considered the ideal instrument for destroying a ballistic missile. With its inherent speed, no recoil, and extremely long range, the laser offers the potential to destroy a missile during its boost phase keep the possible nuclear, biological, or chemical warhead 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 that is 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. The laser disables the missile by concentrating its energy on certain parts of the missile and holding the beam steady for enough time to heat the material. The effectiveness of the laser depends on the beam power, pulse duration, wavelength, air pressure, missile material, and skin thickness.[16] If the laser could specifically target the electronic circuits, which are used for guidance control, the missile would be incapable of staying on course.[17] These circuits are relatively easy to destroy but difficult to precisely target. Another kill mechanism is to vaporize 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 the skin around the fuel tank to fail. This type of failure mechanism results in a rupture of the missile due to its internal pressure and requires the least amount of laser energy to destroy a missile.[18]

How much energy is required to rupture the skin of a missile depends on the missile material and thickness.[19] Table 6 presents a comparison of different ballistic missiles are compared to their range, burn time, skin material, and skin thickness. The energy from the laser must be focused on the target long enough for the 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 cm^2, though the exact fluence value varies slightly for each missile. [20]

Table 6. Missile Vulnerability Parameters[21]

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

The energy requirements described above are the amounts that must be absorbed by the missile. If calculations are made based on the missile skin having a 90 percent reflectivity (meaning that only 10 percent of the laser energy on target is absorbed), the laser fluence on the missile would need to be ten times greater.[22] Yet, laser weapons will be required to produce even greater amounts because of the energy that is lost to atmospheric absorption, thermal blooming, laser beam jitter, and pointing errors.

Notes

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

[2] "Ballistic Missiles Within Easy Reach for Many Nations," *Washington Post*, 23 September 1997.

[3] Spector, 13.

[4] "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.

[5] Ibid.

[6] 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.

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[7] "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.

[8] William Van Cleave, "The Role of Active Defense," in *Security Strategy and Missile Defense*, ed. Robert L. Pfaltzgraff, Jr., (Hollis, N.H.: Puritan Press, 1995), 101.

[9] Spector, 16-17.

[10] Ibid.

[11] Ibid., 13-14.

[12] "The Threat is Real and Growing."

[13] "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.

[14] Ibid.

[15] "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.

[16] Major General Bengt Anderberg and Myron Wolbarsht, *Laser Weapons: The Dawn of a New Military Age* (New York: Plenum Press, 1992), 114.

[17] Kosta Tsipis, "Laser Weapons," *Scientific American*, December 1981, 55.

[18] Geoffrey E. Forden, "The Airborne Laser," *IEEE Spectrum*, September 1997, 46.

[19] Major Michael J. Muolo, *Space Handbook*, vol. 2, Air University Report AU-18, (Maxwell AFB, Ala.: Air University Press, December 1993), 286-287.

[20] USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century*, Directed Energy Volume (Washington, D.C.: Department of the Air Force, September 1996), 24.

[21] Forden, 47.

[22] Ibid.

Chapter 4

Current State of Laser Weapon Technology

High-energy lasers, with their ability to destroy a missile at the speed of light, are extremely attractive weapons against ballistic missiles. With the development of the first lasers in the early sixties, military scientists have been "pushing the outer envelope" of laser technology to achieve greater laser power, better optics, and improved target acquisition, tracking and pointing technologies. This overview is critical to understanding the technology risks 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 which 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 being considered for weapons were actually designed and built in the pioneering days of the laser from early 1960s to late 1970s.[1]

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 and provide the energy for the laser.[2] 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 wavelength is between 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.[3] This laser is the leading contender for the Space-Based Laser (SBL) program.

The Ballistic Missile Defense Organization (BMDO) has continued to support the hydrogen fluoride laser for space-based defenses.[4] 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 megawatt power in a low-pressure, simulated space environment.[5] 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.[6] This laser has been integrated with the Large Advanced Mirror Program, described later, and test fired at the TRW San Juan Capistrano test facility in California.[7]

Deuterium Fluoride Laser

The deuterium fluoride laser operates with basically the same physics principles as the hydrogen fluoride system. 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.[8] The main 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 capable of power in excess of one megawatt.[9] The system was first operational in 1980 and since then has accumulated over 3600 seconds of lasing time.[10] This laser system has been integrated with a system called the SEALITE Beam Director, a large pointing telescope for high-energy lasers, and successfully shot down a rocket at the U.S. Army's High-Energy Laser Systems Test Facility at the White Sands Missile Range in 1996.[11]

Chemical Oxygen Iodine Laser

Another relatively new and promising laser, the chemical oxygen iodine laser, or COIL, has unique features. COIL was first demonstrated at the Air Force Weapons Laboratory in 1978. The lasing action is produced by a chemical reaction of chlorine and hydrogen peroxide. Excited oxygen atoms transfer their energy to iodine atoms, which then raise the iodine atoms to an excited state. The excited iodine atom is responsible for lasing at a wavelength of 1.3 microns, which is a wavelength that is shorter than 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.[12] Also, this wavelength of light transmits through the atmosphere with less loss due to water vapor absorption than the hydrogen fluoride laser.[13] These advantages have accelerated the funding and development of this laser.

This laser was selected by the Air Force for the Airborne Laser missile defense system. A COIL placed in the rear of a 747 will be the "killing" beam. In a test of the COIL conducted by TRW in August 1996, it produced a beam in the range of hundreds of kilowatts which lasted several seconds.[14]

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, they also relay the laser energy and, when required, correct for any atmospheric turbulence which 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 will distort and degrade any laser but is especially severe for the shorter wavelength lasers, such as COIL.[15] These systems will require sophisticated optics in order to "pre-compensate" the laser beam for atmospheric turbulence. To pre-shape the laser beam, an adaptive optics technique is used. Over the past several years, the Air Force's Phillips Laboratory has made significant strides in adaptive optics.[16]

Adaptive optics systems 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. The laser beam is scattered by the atmosphere and this 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 actuator motors 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.[17]

The Phillips Laboratory's Starfire Optical Range has successfully demonstrated this 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, 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.[18] This seminal development has possibly been the most significant revolutionary improvement in optical technology in the past ten years.[19]

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 demonstrated 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.[20] The Large Advanced Mirror Program (LAMP) designed and fabricated a four-meter diameter lightweight, segmented mirror.[21] This mirror consists of seven separate segments that are connected to a common bulkhead. The advantages of building a large mirror in segments are that the manufacturing, machining, and handling of the smaller segments are less complicated than one large mirror and each segment can be repositioned with small actuator motors to slightly adjust the surface of the mirror. The finished mirror was of the required optical figure and surface quality for a space-based laser application.[22]

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 and timing requirements for each component are stringent due to the distances between the weapon and the target.[23]

A significant amount of effort went into both space and ground programs in all of these areas. Space experiments are critical to any high-energy laser weapon system because they not only demonstrate high-risk technologies, but do so in the actual operational environment. However, the space programs suffered from high costs and the space shuttle Challenger accident.[24] Many were terminated or had their scope reduced due to insufficient funding, though two highly successful space experiments were completed in 1990. The Relay Mirror Experiment demonstrated high accuracy pointing, laser beam stability and long duration beam relays. This technology is key for any weapon architecture that requires relay mirrors in space. Another successful test was the called the Low Power Atmospheric Compensation Experiment, which demonstrated compensation technology for laser beam distortions that occur due to atmospheric turbulence.

A number of the space experiments were cancelled 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 key technologies essential for the space weapon platform to maintain the laser beam on the target despite the large vibrations induced by the high-energy chemical laser. The Rapid Retargeting/Precision Pointing simulator was designed to replicate the dynamic environment of large space structures. This technology is especially critical for a space-based laser. Scientists tested methods to stabilize the laser energy beam, maintain accuracy, and rapidly retarget. Within the constraints of a ground environment, the techniques developed should be applicable to space systems.[25] 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 improved the pointing stability even more.[26] To understand the technology necessary to control large structures, the Structure and Pointing Integrated Control Experiment (SPICE) was developed to demonstrate active, adaptive control of large optical structures.[27]

The tests, experiments and demonstrations described above represent the state-of-the-art today. The next issues are how to fit these into an architecture, and how much further to push the technology.

Notes

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[2] Ibid., 484, 497.

[3] Crockett L. Grabbe, "Physics of a ballistic missile defense: The chemical laser boost-phase defense," *American Journal of Physics*, 56(1), January 1988, 32.

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[6] US General Accounting Office Report, "Ballistic Missile Defense – Information on Directed Energy Programs for FY 1985 Through 1993," GAO/NSIAD-93-182, (Washington, D.C.: Government Printing Office, June 1993), 20.

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

[8] Geoffrey E. Forden, "The Airborne Laser," *IEEE Spectrum*, September 1997, 42.

[9] "Science and Technology of Directed Energy Weapons," 60.

[10] "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.

[11] Forden, 45.

[12] Ibid., 42.

[13] R. Benedict, et al., et al., *Final Report of the Laser Mission Study*. PL-TR-93-1044, (Kirtland AFB, N.M.: Phillips Laboratory, July 1994), 15-16.

[14] Forden, 45.

[15] Benedict, 17.

[16] John W. Hardy, "Adaptive Optics," *Scientific American*, June 1994, 60-65.

[17] Ibid.

[18] "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.

[19] Benedict, 19.

[20] Schafer Corporation, "Space-based Laser: Pioneering Tomorrow's Defense," CD-ROM, 1997.

[21] US General Accounting Office Report, 21.

[22] "Space-Based Laser Fact Sheet."

[23] US General Accounting Office Report, 35.

[24] Ibid., 36-37.

[25] Ibid.

[26] Ibid., 38.

[27] Schafer Corporation.

Chapter 5

Space-Based Laser Architecture

A space-based weapon system possesses a unique capability 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, in a low earth orbit, the distance from the laser to the missile is decreased but more weapon platforms are required to provide global coverage. Each alternative presents a range of strengths and weaknesses concerning effectiveness, technical feasibility, and cost.

The notion 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.[1] The original architectures were designed to destroy Soviet ICBMs in the boost phase before their independent warheads could deploy. 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 laser platform's requirements to be up to 30 megawatts of laser power and a ten-meter diameter primary mirror.[2]

Following the collapse of the USSR and the reduced risk of an all out strategic nuclear attack, space-based laser concepts have redirected their focus to defending against theater ballistic missiles. Today's theater ballistic missile threat involves fewer missiles launched simultaneously and rather than concentrating on long-range missiles from the USSR, the system must destroy short-range missiles launched from anywhere in the world. This makes the laser weapon's requirements less stressing than in the SDI scenario of the 1980s.[3]

Operational Concept

The Ballistic Missile Defense Organization has completed several studies that considered the space-based laser's orbital altitude, laser power and optics requirements, and number of platforms. They determined the best approach is for the system to consist of 20 space-based laser platforms and operate at an inclination of 40 degrees, 1300 kilometers above the surface of the earth. In this orbit, the space-based laser can destroy the missile in a range of 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 12 platforms for partial coverage of the earth, and eventually a constellation of 20 satellites will provide nearly full protection from theater ballistic missile attacks.[4]

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, operating at 2.7 microns. A primary mirror, with a diameter of eight meters, will utilize super-reflective coatings which will allow it to operate without active cooling despite the tremendous heat load from the laser energy.[5] One estimate for the laser power is eight megawatts.[6] 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 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.[7] For comparison, the Hubble Space Telescope is 11,000 kilograms and Skylab was 93,000 kilograms.[8]

Architecture Evaluation

The space-based laser concept must overcome several significant technical 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 capable of only a limited number of shots. 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.[9] Another potential hurdle is getting these platforms into space.

Technology Assessment

Individual pieces of technology have been developed, but 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. Regarding the 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 the 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.[10] The demonstrator will consist of a high-energy hydrogen fluoride laser operating at one-third the beam 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, with an optimistically planned launch date of 2005, will span over three years.[11]

If the laser demonstrator comes to fruition, the space-based laser program will achieve a significant boost in its maturity and feasibility. The previous technology programs have demonstrated that most of the basic engineering issues can be overcome. The remaining concerns for the platforms are system engineering and integrating the subsystems and making them work together in a space environment. These steps are essential before the US can commit to a space-based laser system. The engineering required for the laser demonstrator would address most aspects of the laser platform. One significant additional 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 payload capacity to place 22,000 kilograms into low earth orbit.[12] If the laser platform dimensions cannot be reduced, this limited payload size will require each laser platform to be launched on two rockets and assembled in space, or a new class of launch vehicles must be developed and fielded. However, a new launch vehicle specifically for the space-based laser is not likely given how long the DOD has been trying to replace the Titan IV.[13] 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 that assembling the system in space is achievable. 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 Technology Assessment

Systems	Feasibility	Maturity
High-Energy Laser	4 (no breakthroughs required)	4 (less than five years to field)
Optical Components	4 (no breakthroughs required	4 (less than five years to field)
ATP/FC	4 (no breakthroughs required	4 (less than five years to field)
Integration	3 (major challenges remain)	2 (ten to fifteen years to field)
Launch	3 (major challenges remain)	2 (ten to fifteen years to field)

Note: Assessment assumes successful 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: 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. This latest round of cost estimates range from $17 billion to $29 billion for 20 platforms, including the work required for the remaining development efforts.[14]

Compared to previous space programs, the above space-based laser cost estimates are exceptionally low and probably unrealistic. From previous space programs, the average cost of military satellites ranges from $50,000 to $150,000 per kilogram. In the case of the estimated cost for the space-based laser architecture, the entire constellation's estimated weight is 700,000 kilograms (20 platforms at 35,000 kilograms each). Based on the historical "average" cost of $100,000 per kilogram, the costs for the platforms are $70 billion. The technology readiness level, described in an earlier section, is rated a 7, which means that laser demonstrator has been tested in space, and therefore, the cost estimate needs to be increased by 10 percent. When launch costs are included, based on the new launch vehicle's proposed costs of $5650 per kilogram, the total cost rises to $81 billion. With this rough estimate, we have a means to compare the space-based laser architecture with the following two architectures.

Technology Development Programs

Although the space-based laser components are relatively mature, several new technologies offer significant benefits. In the near term, resources must be focused on the laser demonstrator because without a successful demonstration of a high-energy laser weapon system in space, deploying this weapon system is extremely risky. The various component technologies which make up a space-based laser have been studied and tested since the 1970s, any remaining uncertainties lie in the system engineering aspects of building a space-worthy platform.

Investments in several key technologies could produce performance and cost improvements in the long run. Three areas of technology could improve the space-based laser concept – 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 and produces a wavelength of 1.3 microns.[15] A second alternative is the Chemical Oxygen Iodine Laser which 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 down to 0.8 microns.[16]

In addition to improving lasers, advancing the state of the art in optics has the potential of a high payoff. If the laser beam director had a larger primary mirror, the amount of energy 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 reduces costs.[17] Large optical systems are described in depth in the following section.

The final area for additional investment is in the pointing and tracking technology. If pointing accuracy were improved, the amount of "smearing" caused by beam jitter would decrease, which has the same effect as larger optics or a more powerful laser. Improved pointing could be accomplished by a variety of means. A detailed analysis would point out where to focus our efforts to improve pointing technology.

Notes

[1] The original notions for the Alpha laser, LODE optics and Talon Gold ATP/FC were technology development programs for an antisatellite SBL concept. Based on author's personal experience when assigned to the Space Laser Program Office, Los Angeles AFB, Ca. from 1981 to 1983.

[2] "Science and Technology of Directed Energy Weapons," American Physical Society Study, *Reviews of Modern Physics*, vol. 59, Part II, July 1987, 55.

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

[4] Schafer Corporation, "Space-based Laser: Pioneering Tomorrow's Defense," CD-ROM, 1997.

[5] Ibid.

[6] USAF Scientific Advisory Board, 24.

[7] Schafer Corporation.

[8] Ibid.

[9] USAF Scientific Advisory Board, 23.

[10] Schafer Corporation.

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Notes

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

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[14] Dr. Marc Hallada and Dr. Dustin Johnston, Schafer Corporation, interviewed by author, 1 November 1997.

[15] USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century*, Directed Energy Volume. (Washington, D.C.: USAF Scientific Advisory Board, September 1996), 25.

[16] Ibid.

[17] Ibid., 24.

Chapter 6

Ground-Based Laser System 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 size a laser platform to 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 anomalies occur within the ground laser systems, the equipment is readily accessible without having to plan, fund, and recover the satellite from orbit. Also, the ground laser and beam director are not as constrained by diameter, weight, or volume as is the case for a space platform that requires 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 target. 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.[1] Since 1990, the ground-based laser architecture has not been revised to consider a scaled-down version given the new threat requirements. As an example of a Strategic Defense Initiative-type scenario for the ground-based laser system, 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 scenario drove the architecture requirements to have in place at least 150 ground telescopes and 50 powerful ground lasers.[2] Since then the threat has changed dramatically and so have the technologies. This section presents an architecture given this reduced threat and an evaluation of the technical 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. As shown in figure below, the 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 must be either a deuterium fluoride or COIL type device (at the wavelength of a hydrogen fluoride laser, the laser beam is largely absorbed by the atmosphere).

Since poor weather, such as clouds, wind, and pollution, can cause laser distortions, the ground lasers would 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 50 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.[3]

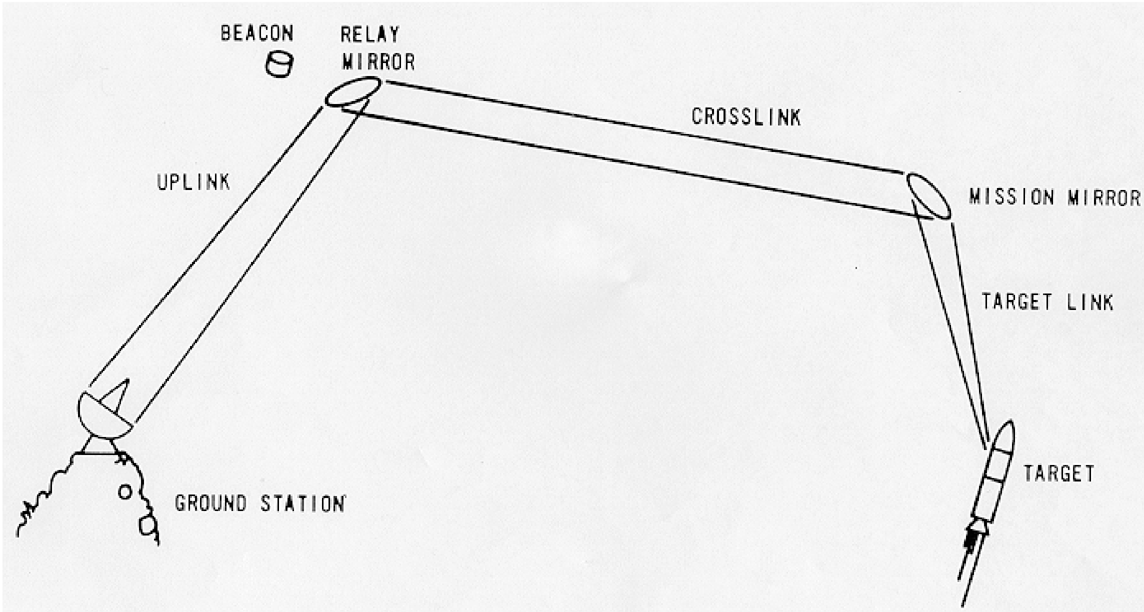

Figure 1. Ground-Based Laser Architecture Concept[4]

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 would be the preferred laser because of 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 would need to be substantially greater than the space-based laser, since there would be some losses due to atmospheric transmission and thermal blooming in addition to the longer ranges that the beam must travel.

The ground laser would be integrated with a beam director resembling the SEALITE system discussed previously. 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.[5] It would also include sensors and fast beam steering mirrors to compensate for the atmosphere, which are analogous to the Starfire adaptive optics system. It is worth noting that the technology demonstrated at Starfire has overcome one of the fundamental concerns for achieving a ground-based laser system.

Once the laser beam is produced, the next challenge is to use adaptive optics to compensate for atmospheric distortion. The ground-based laser will use a “beacon” system next to the relay mirror to transmit a low power laser beam down to the ground to produce the guide star. As with Starfire, the laser beam is scattered by the atmosphere, and after this scattering radiation is measured, the system knows just how much the atmosphere would distort the high-energy laser. Feeding the information into a control system, a deformable mirror on the ground would change the shape of its’ surface to compensate for the distortion. This technique permits the high-energy to be “pre-distorted” so it can remain coherent as it passes through the atmosphere.[6]

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 can affect the diameter required for the beam director’s primary mirror, relay mirrors, and mission mirrors, and as well as the numbers of space mirror. As an example of just one of many trades, the relay mirror could be positioned either in geosynchronous earth orbit, highly elliptical orbit, or medium earth orbit. It would “catch” the laser beam and then relay it to the mission mirror. At a geosynchronous or highly elliptical orbit altitude, the relay mirror would have to be a larger diameter than at medium earth orbit. Yet, at geosynchronous orbit the number of mirrors required to “cover the world” is far less than medium earth orbit and could effectively reduce the system complexity. For this architecture, a total of four geosynchronous earth orbit relay mirrors 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.

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 allows for a smaller diameter mission mirror and a smaller laser spot on its intended target. As with the relay mirrors, the mission mirror parameters depend on multiple factors including the laser wavelength, relay mirror diameter, mission mirror diameter, and altitude of each mirror.[7] One particularly intriguing concept for the mission mirror is called 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 it receives the laser beam directly into its primary mirror. This design reduces laser power losses associated with incidence angles less than 90 degrees, which essentially ensures that almost all 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.[8] To achieve the same robustness as the space-based laser architecture for theater ballistic missile defense, 20 mission mirrors are required.[9]

Several assumptions were necessary in order to estimate the size and power of the laser and diameter and weight of the space-based mirrors. These are outlined in the table below.

Table 8. Ground-Based Laser System Parameters[10]

System Parameters	Comments
Beam Director	8 meter primary
Relay Mirrors	4 mirrors in GEO, 20 meter diameter, 40,000 kilometers from ground laser
Mission Mirrors	20 mirrors in LEO, 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 MW based on ranges between laser and space mirrors and power loss values

In addition to the large primary mirrors, each mirror satellite would also include an active control system of 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).[11] Lightweight mirror technology, similar to NASA's Next Generation Space Telescope (NGST), would enable the mirror weight to be kept low.[12] Based on this technology, the relay mirror spacecraft would weigh an estimated 34,000 kilograms. The mission mirror satellites, with their dual telescope design, would be 8,500 kilograms.

Architecture Evaluation

The ground laser and large space mirrors must overcome some tremendous obstacles that are not encountered with the space-based laser architecture. For instance, the longer ranges between the laser and the target dramatically increase the laser power requirement. Also, the atmospheric losses will be larger than the space-based laser system, which in turn drive not only the laser power requirement, but also the adaptive optics that are needed to control the laser beam quality.[13] Furthermore, the large space mirrors must be built to high optical quality standards and be susceptible to space debris and high-energy space particles.[14]

Technology Assessment

The technology challenges associated with the ground-based laser system focus on the optics (fabricating large mirrors, deploying large mirror systems in space, and applying optical coatings to mirrors) and achieving the output power of the ground laser. Since the 1980s, the Strategic Defense Initiative Organization and later the Ballistic Missile Defense Organization have studied large space mirrors with the Large Optics Demonstration Experiment and Large Advanced Mirror Program, as described previously. Currently, NASA is investigating new concepts for Next Generation Space Telescope. The primary mirror for this telescope will be an eight-meter diameter structure, either deployable or inflatable.[15] 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.[16]

To achieve this demanding requirement, the telescope design incorporates low density, thin mirrors that are unfolded in space similar to flower petals opening. 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 using a deformable mirror concept developed by the Strategic Defense Initiative Organization. NASA has implemented an aggressive risk reduction program to demonstrate these technologies.[17] Much of the NASA mirror technology is applicable to the ground-based laser's space mirrors, but ground-based laser's relay mirrors require diameters of 20 meters and, therefore, a significant increase in technical difficulty. Even with the NASA technology, the relay mirror weight is far beyond the current launch vehicle capacity, particularly if put in geosynchronous orbit. Either a new launch vehicle must be built, even larger than required for the space-based laser architecture, or another technical leap is required to significantly reduce the relay mirror's weight.

In addition to the tremendous mirror size, the mirror coatings, for both space and ground are unique to the ground-based laser problem because they must be capable of withstanding a large amount of 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 still remain intact. The high-energy laser programs such as MIRACL and Alpha have a long experience with this type of high reflectivity coating. Previous studies concluded that the optical coating processes would meet the performance requirements of the ground-based laser system.[18]

The power for each ground-based laser at least 25 times greater than what has been demonstrated to date. To achieve this increase in power, multiple lasers must be optically coupled together to produce one powerful beam. Although physically possible, it will take years to overcome the engineering challenges.

The ground-based laser system architecture's technical feasibility and maturity falls short of the space-based laser system. Achieving a 20-meter diameter relay mirror will require major technical breakthroughs to reduce the weight and volume sufficiently to allow the platform to fit on an existing launch vehicle. The Chemical Oxygen Iodine Laser system, though not constrained by weight or volume as is case with the space-based laser, must be capable of much more power than has been demonstrated so far.

Table 9. SBL, GBL Technology 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

Table 10. SBL, GBL Technology 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)	3 (five to ten 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	12

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 for the ground-based laser architecture are divided into on-orbit segment and ground segment costs. These estimates are based only on DOD experience, but it is instructive to discuss NASA's projection for the Next Generation Space Telescope program.

Recently, NASA issued a cost assessment paper describing why they believe the new telescope, with its aperture of eight meters, will cost only about 25 percent of the Hubble space telescope, with an aperture three times smaller. They cite several factors, including improved mirror fabrication facilities, improved computer processing, and better organizational structure, as a means to program reduce costs. NASA's goal is for the entire program to cost $500 million including research, development, test, and launch.[19] Since some of the research and development efforts for the one-of-a-kind Next Generation Space Telescope may benefit the space mirror systems for this architecture, the ground-based laser system costs may be lower. Despite this potential cost improvement, to be consistent with the space-based laser system estimate, the space components will be estimated at $100,000 per kilogram.

First consider the space mirrors with the constellation's estimated weight of 306,000 kilograms (four relay mirror platforms at 34,000 kilograms each and 20 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 technology readiness level described in a previous section, the ground-based laser architecture is rated a 2, which means that the conceptual design has been formulated. This rating requires another 25 percent factor added on to the estimate for a total of $38.25 billion. Next consider the launch costs. When these expenses are included, based on the Evolved Expendable Launch Vehicle's proposed costs of $5650 per kilogram, the total space segment cost rises to $40 billion.

Now compare the estimated cost for the ground portion of the ground-based laser architecture. One of the stronger arguments for this architecture over the space-based laser approach is that it will decrease on-orbit weight and therefore will reduce the system cost. What is missing from this analysis is the cost of the ground segment. In the past, high-energy lasers were built for experimental purposes rather than operational weapon systems. Projecting a laser system cost estimate from an experimental system does not take into consideration the additional specifications that an operational system would require. Unfortunately, the only "operational" system to base this estimate on is the Airborne Laser (ABL) program, which is currently 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 and not on the ground. However, this difference is significant because of the requirements for the airborne system to be lightweight. It is also constrained by the volume of the aircraft. Considering the projected cost for each ABL aircraft is $1 billion, the cost per watt of output power is $330 per watt.[20] If an optimistic 50 percent of the cost was for making the system fit within the aircraft, a constraint not required for a ground-based laser, the cost per watt is now down to $165. With this cost estimate, each ground laser site would cost around $4.13 billion, with five sites costing $20.6 billion. This places the entire ground-based laser architecture, including space and ground segments, at $60.6 billion.

Another cost comparison can be derived from an estimate for a ground-based laser anti-satellite system.[21] Extrapolating linearly to the laser's power requirement for missile defense places each ground site at over $25 billion and five sites would be $125 billion. Based on this number, the total system would cost $165 billion. The large variation between the two estimates for the ground-based system makes it difficult to recommend this architecture as more cost effective over the space-based laser approach.

Table 11. SBL, GBL Cost Comparisons

Cost Range	SBL ($ Billion)	GBL ($ Billion)
Low Estimate	17	61
High Estimate	81	165

Clearly, the great technical challenges associated with achieving the laser output power and building and placing into geosynchronous orbit the 20-meter diameter relay mirrors on top of the significant cost, drive the appraisal of this architecture to the point where it is less attractive than the space-based laser concept.

Technology Development Programs

Despite this assessment, a few promising technologies could be considered for long-term investment. The greatest challenge facing this architecture is achieving the high power laser and reducing the ground laser's cost. Revolutionary concepts need to be investigated and funded which look at different laser options or optically coupling multiple lasers together. Theoretically, multiple lasers could be optically coupled together and projected as one intense beam from the ground to the relay mirror. Other approaches are possible including the use of adaptive optics to combine the beams from multiple apertures.[22] These techniques are still at their infancy and clearly require more laboratory analysis and demonstrations.

One of the more promising areas for technology investment is real-time holography to correct for wavefront errors in large mirrors. Currently, large mirrors are manufactured to stringent surface quality requirements to achieve the highest quality surface through grinding and polishing, while maintaining that surface during launch, deployment, and operation. Yet, when mirrors are constructed of lightweight materials, the optical quality cannot be maintained except through complex mechanical systems. To alleviate this problem, Phillips Laboratory is conducting research in a real-time holographic compensation system. This concept would allow the mirror to be far less than perfect, then use an all-optical process to compensate for the surface quality. The outcome of the research could have far reaching ramifications not only for a ground-based laser system, but also for reconnaissance, remote sensing, and astronomical satellites.[23]

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 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 by the Air Force, NASA could incorporate ground-based laser's mirror requirements that are not currently being addressed. Finally, a NASA/AF partnership is even more important with the architecture of space-based lasers and orbiting mirrors.

Notes

[1] Numerous architecture studies have been performed for a ground-based laser system. 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.

[2] "Science and Technology of Directed Energy Weapons," American Physical Society Study, *Reviews of Modern Physics*, vol. 59, Part II, July 1987, 210.

[3] 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, Vir.: Defense Nuclear Agency) June 1991, B-45.

[4] Figure provided by Phillips Laboratory, Kirtland AFB, N.M.

[5] V. Krabbendam and T. Sebring, *Ground-based Laser System Optical Component Producibility Study – Executive Summary*, RADC-TR-90-355 (Griffiss AFB, N.Y.: Rome Air Development Center, 1990), 3.

Notes

[6] John W. Hardy, "Adaptive Optics," *Scientific American*, June 1994, 60-65.

[7] Dr. Marc Hallada and Dr. Dustin Johnston, Schafer Corporation, interviewed by author, 1 November 1997.

[8] Phillips Laboratory, Kirtland AFB, N.M., interviewed by author, 31 October 1997.

[9] Estimate based on 2000 km altitude and 4000 km range from mission mirror to target. Verified by U.S. Air Force Academy Department of Physics, interviewed 26 November 1997.

[10] Estimates were derived by author and confirmed with Phillips Laboratory, Kirtland AFB, N.M. 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.

[11] Krabbendam and Sebring, 3.

[12] The mirror weight estimates for deployable mirrors vary greatly. One estimate provided by Phillips Laboratory, Kirtland AFB, N.M. 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 was from Richard Dyer, Schafer Corporation, who was on NASA's NGST independent review team. To be conservative, I used $D^{2.7}$ as the scale factor and included the mirror supporting mass in addition to the mirror. I also 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
+ 20% of 5,400 (for transfer optics)
+ 2,000 kg (for spacecraft)
=8,500 kg

[13] Ulrich and Morgan, C-105.

[14] "Science and Technology of Directed Energy Weapons," 8.

[15] Ron Cowen, "After Hubble: The Next Generation," *Science News*, 26 April 1997, 262.

[16] 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/.

[17] Stockman, ed.

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[18] 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, N.Y.: Rome Air Development Center, 1990), 4.

[19] 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.

[20] Geoffrey E. Forden, "The Airborne Laser," *IEEE Spectrum*, September 1997. Dr. Forden states that each aircraft costs about $1 B and estimates the output power to be 3 MW.

[21] Phillips Laboratory, Kirtland AFB, N.M., interviewed by author, 1 December 1997. The estimate was based on a GBL ASAT system with a brightness of 1.0×10^{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. My extrapolation assumed a brightness factor approximately 20 times greater and therefore a cost 20 times higher.

[22] "Science and Technology of Directed Energy Weapons," 7.

[23] 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, N.M.: Phillips Laboratory, 1997).

Chapter 7

Space-Based Laser "Plus" Architecture

Perhaps the most intriguing of the three concepts, space-based laser weapons in conjunction with large orbiting mirrors or space-based laser "plus", offers the potential to reduce the number of space-based laser platforms, reduce on-orbit weight and therefore costs, while providing a more robust constellation. This architecture is based on decreasing the number of platforms and inserting bifocal mirrors into the same orbit as the lasers.

As with the first concept, placing the weapon in orbit takes advantage of the unique aspects of space. Unlike ground-based laser systems, the space-based laser is able to cover a large theater of operations with the weapon directly, which 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 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 as the distance between the laser and it's target gets longer. In addition, the platform's mechanical pumps and cooling systems create vibrations which 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 larger aperture primary mirror.

A more attractive alternative to compensate for this intensity loss due to a higher orbit and beam jitter is to have the laser platform fire into space mirrors. This concept, which was explored briefly in the 1980s, combines the strengths of both previously described architectures to produce an effective and technically achievable system at the least cost.[1]

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 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 either fire directly at the missile or relay the laser beam through the mirror depending on where the threat 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 since 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.[2]

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.

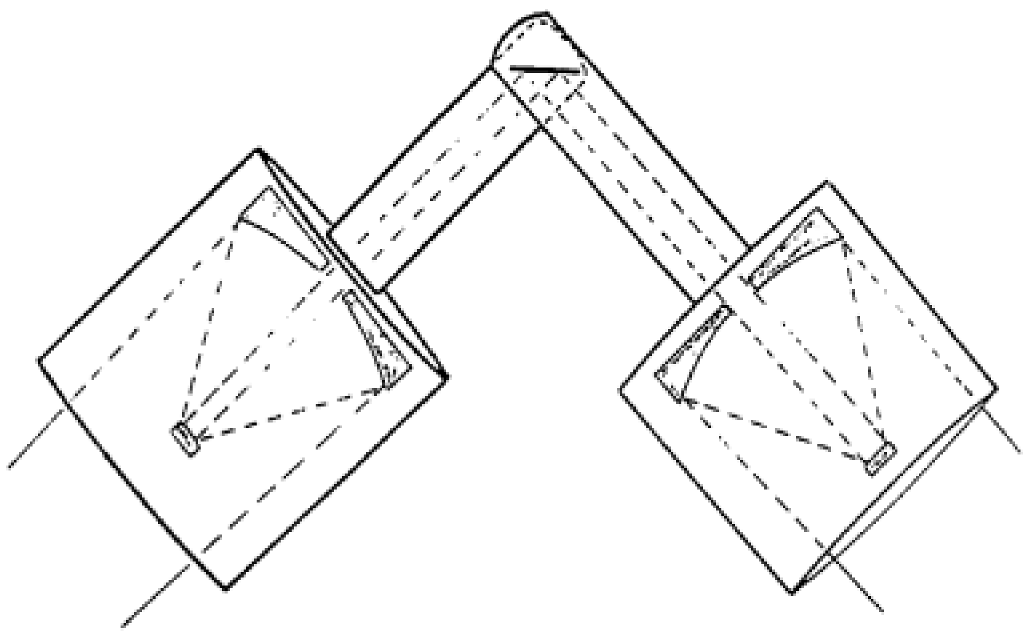

Figure 2. Bifocal Space Mirror Design[3]

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 resulted in several advantages: a lower overall weight of the payloads required on-orbit, a reduced aperture and laser beam jitter requirement of the space-based laser, and a reduced vulnerability of the overall system.[4] Although this study assumed an SDI-type missile threat scenario, the results for a theater ballistic threat will be similar. In comparison with the previous two concepts, the technology requirements for this architecture are far less demanding.

Technology Assessment

One distinct advantage of this architecture concept is the possibility of reducing the weight and expense of the system. Instead of 20 laser platforms, the concept requires only ten and the addition of orbiting mission mirrors. The combined weight of the space-based lasers and mission mirrors is approximately 40 percent less than the space-based laser-only architecture. Lightweight mirror technology, being developed independently by NASA and Air Force's Phillips Laboratory, would enable the mission mirror weight to be kept low and also to fit on an existing launch vehicle. With this improved technology, the eight-meter bifocal mirror systems would weigh 8,500 kilograms each.[5]

Another potential benefit of the SBL "Plus" architecture is to decrease the size of the space-based laser. As with the SBL-only system, the laser platforms will require a new launch vehicle to place these systems into orbit. An alternative is to make the laser platform's aperture smaller and increase the number of mission mirrors in orbit. The 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 laser platform's jitter. Another option 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 would compensate for the lower laser power, providing the same laser intensity on the target. These are just two examples of the increased flexibility provided by adding mission mirrors to the architecture. Any tradeoffs must balance the size and cost of the laser platform and mission mirrors with the goal of increasing the technical feasibility and allowing each system to fit on an Evolved Expendable Launch Vehicle.

Table 12. SBL, GBL, and SBL "Plus" Technology 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: Assessment assumes successful space-based laser readiness demonstrator and reducing 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 and the technical assessment assumes that the demonstrator is successfully funded, built, and tested. In addition, this architecture also uses the intriguing concept of a bifocal mission mirror. It consists of two connected telescopes, coupled by smaller mirrors that 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. From there the beam is transferred to the second telescope, the outgoing transmitter, which sends it to the missile.[6]

Table 13. SBL, GBL, and SBL "Plus" Technology 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)	3 (five to ten 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	12	22

Note: Assessment assumes successful space-based laser readiness demonstrator and reducing the size of the space-based laser platform

Cost Estimate

While the SBL "Plus" has technical 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 how much this system will cost in comparison to the other architectures.

The 20 platform space-based laser-only constellation will cost between $17 billion to $29 billion based on the estimates by the DOD. Yet, an analysis based on weight on-orbit yields a more realistic cost estimate of $81 billion. This latter cost will be used for the comparison. As described in the previous section, the ground-based laser architecture is estimated to cost as much as $165 billion.

The cost estimate for this 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 50 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 costs for the systems would be $43.5 billion. Since the laser demonstrator will test only the critical laser hardware in space but not the bifocal mirrors, the space-based laser "plus" architecture merits a technology readiness level (described in a previous section) of 5. Attaching this rating requires another 10 percent factor added on to the estimate. When launch costs are included (based on the Evolved Expendable Launch Vehicle's proposed costs of $5650 per kilogram), the total cost rises to $50.3 billion. These costs are about 40 percent less than the cost of the space-based laser-only option and significantly lower than the ground-based laser system.

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

SBL	GBL	SBL "Plus"
$81 billion	$165 billion	$50 billion

Technology Development Programs

For this concept, the appropriate technology development programs are a mix of the previous two architecture recommendations. Clearly, the Readiness Demonstrator is essential for without an on-orbit test of a subscale system, numerous and challenging system engineering issues remain open. Including a subscale bifocal mirror in space with the laser demonstrator program offers several unique opportunities. Furthermore, the research being conducted by Phillips Laboratory on holographic wavefront correction may allow the large bifocal mirrors to have less than perfect shape, while using an all-optical process to compensate for the mirror's surface quality.

A combined bifocal mirror demonstration program between the Air Force and NASA and perhaps the National Reconnaissance Office could help share of the cost and more importantly, build strong bureaucratic support for all the programs. From past experiences, consolidating DOD and NASA programs are not always popular but can be cost effective if planned carefully.[7] By far, the optimum demonstration would include a bifocal mirror that is launched into space concurrently with the laser demonstrator. If funding was made available for the bifocal mirror satellite to be built and launched near the launch of the demonstrator, the on-orbit tests of the high-energy laser could be conducted in conjunction with the mirror. The Air Force could demonstrate the space-based laser with orbiting mirrors architecture, NASA would be able to demonstrate a space-qualified deployable mirror for the Next Generation Space Telescope, and the National Reconnaissance Office could use this "space-qualified" technology for future imaging satellites.

Notes

[1] Lawrence Sher and Capt Stephan McNamara, "Relay Mirrors for Space Based Lasers," Research Report, *Laser Digest*, AFWL-TR-88-68, Volume VI (Kirtland AFB, N.M.: Air Force Weapons Lab, May 1989).

[2] Phillips Laboratory, Kirtland AFB, N.M., interviewed by author, 31 October 1997.

[3] Figure provided by Schafer Corporation. Used with permission.

[4] 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, N.M.: Air Force Weapons Lab, May 1989).

[5] The mirror weight estimates for deployable mirrors vary greatly. One estimate provided by Phillips Laboratory, Kirtland AFB, N.M. 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 was from Richard Dyer, Schafer Corporation, who was on NASA's NGST independent review team. To be conservative, I used $D^{2.7}$ as the scale factor and included the mirror supporting mass in addition to the mirror. I also 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 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
+ 20% of 5,400 (for transfer optics)
+ 2,000 kg (for spacecraft)
=8,500 kg

[6] Phillips Laboratory, Kirtland AFB, N.M., interviewed by author, 31 October 1997.

[7] 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.

Chapter 8

Conclusion

The main purpose of this paper is to explain three alternative architectures for high-energy laser space systems. The current space-based laser architecture is based on years of studies, analyses, technology demonstrations, and space experiments. Lasers such as MIRACL and Alpha demonstrate that the technology is within our grasp to achieve the necessary laser power levels. 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 technology to control and stabilize large space structures. Finally, the Space-Based Laser Readiness Demonstrator will bring together the individually tested systems into an integrated package and demonstrate that the system works in space.

The second alternative, the ground-based laser system architecture, though attractive in some aspects, is far less mature and potentially far more expensive than the space-based laser concept. The driving requirement, both technical and cost, is the high-energy ground laser. This system must be capable of producing a laser power up to 25 times greater than what has been demonstrated to date. Although technically feasible to achieve, the system costs could be significantly higher than the space-based laser system.

From the ground laser telescope, the laser beam would be directed to relay and mission mirrors in space. The relay mirror systems for this concept, with their 20-meter diameters, push the envelope of technology significantly further than the other concepts.

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

This study recommends that the US consider the combination of space-based lasers with orbiting mirrors. In this concept, bifocal mirrors are positioned in orbit between the laser platforms, reducing the number of the heavy space-based lasers and the total system weight and cost. The space-based lasers would either fire directly at the missile or relay the laser energy to a mission mirror. The bifocal mission mirrors would "catch" the laser beam from the laser platform, refocus, and direct it against the missile target. In addition to reducing the number of laser platforms, the laser's jitter requirement could be relieved since the mission mirrors would attenuate some of this jitter. Compared to the space-based laser-only and ground-based laser concepts, this approach is technically far less demanding. The mission mirror size is approximately the same as NASA's Next

Generation Space Telescope. Also, the laser's primary mirror or output power could potentially be reduced from the original space-based laser concept. 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. As with the space-based laser architecture, the Readiness Demonstrator is the key to successfully implementing this approach. If this architecture were selected, the best demonstration would be to include a jointly funded bifocal space mirror concurrently with the laser demonstrator.

Recommendations

The DOD should begin now to incorporate space mirrors into the space-based laser architecture and pursue the following:

1. Conduct a detailed architecture study for a space-based laser system with mission mirrors. Examine the trades between laser power, laser jitter, aperture size, mission mirror size, orbits, weight, and cost.
2. Fund a bifocal mirror program such that it could be launched in conjunction with the Space-Based Laser Readiness Demonstrator. This effort could be to develop a subscale mirror rather than full size. The Ballistic Missile Defense Organization and Air Force should encourage a combined program with NASA and National Reconnaissance Office to test the mirror technology in space. Also, invest jointly with NASA and possibly with the NRO in mirror technology that is being developed for the Next Generation Space Telescope.
3. Investigate ancillary missions for bifocal space mirrors such as high-resolution ground imaging, high-resolution space imaging, and remote sensing.

4. Continue funding the development of Phillip Laboratory's real-time holography to correct for wavefront errors.

In these times of decreasing defense budgets, policy makers must select the laser weapon architecture that is both technically achievable and cost effective. Despite the few advantages of the ground-based laser approach, the optimum path at this point in time is the space-based laser with orbiting mirrors. The results of this study clearly point to this road for the future of high-energy laser weapons.

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
AU	Air University
AWC	Air War College
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

laser. Any of several devices that convert incident electromagnetic radiation of mixed frequencies to one or more discrete frequencies of highly amplified and coherent visible radiation.

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