AU/ACSC/165/1998-04

AIR COMMAND AND STAFF COLLEGE

AIR UNIVERSITY

LASER OPTIONS FOR

NATIONAL MISSILE DEFENSE

by

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A Research Report Submitted to the Faculty

In Partial Fulfillment of the Graduation Requirements

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Maxwell Air Force Base, Alabama

April 1998

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (FROM - TO)
01-04-1998	Thesis	xx-xx-1998 to xx-xx-1998

4. TITLE AND SUBTITLE
Laser Options for National Missile Defense
Unclassified

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Leonard, Steven G. ;

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME AND ADDRESS
Air Command and Staff College
Maxwell AFB, AL36112

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME AND ADDRESS
,

10. SPONSOR/MONITOR'S ACRONYM(S)
11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APUBLIC RELEASE
,

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19. NAME OF RESPONSIBLE PERSON
			Public Release	107	Fenster, Lynn lfenster@dtic.mil
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER
Unclassified	Unclassified	Unclassified			International Area Code Area Code Telephone Number 703767-9007 DSN 427-9007

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39.18

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Preface

This paper was written to increase my knowledge about National Missile Defense and its associated technical, operational and political issues. In the process, I have convinced myself that a reasonable NMD system can be built with full implementation started within the next 10 years. Hopefully, this paper will help convince others.

I wish to acknowledge the help and support of:

Ed Duff and Larry Sher,

Mark Devirgilio,

an excellent Air University Library staff,

and especially my family: Desirée, Dominique, and Erin.

Abstract

The Cold War threat that was characterized by a USSR launch of a large number of ballistic missiles towards the United States has been replaced today by an even less stable ballistic missile security environment. The US National Security Strategy recognizes the existence of threats with both the capability and will to use weapons of mass destruction launched by ballistic missiles. This threat environment coupled with a high leverage to attack ballistic missiles in the boost phase, points to a National Missile Defense (NMD) solution that includes laser weapons.

Four boost-phase laser architectures have been evaluated using NMD technical, operational, fiscal and political criteria. The Space Based Laser (SBL), SBL with Relay Mirrors, Ground Based Laser (GBL) with Relay Mirrors, and Airborne Laser (ABL) with Relay Mirrors each meet the NMD requirements with varying degrees of success. Overall, a Relay Mirror architecture accepting multiple laser sources was found to produce the best NMD boost-phase defense while reducing potential technical, operational, and political issues.

This analysis shows that US Space Command should implement a Relay Mirror architecture with the ability to accept multiple laser sources, such as the planned ABL or a future GBL. This would enable a powerful boost-phase NMD capability with future expandability at minimal cost. Improvements to this architecture could be implemented using SBL, GBL, or ABL sources as NMD or adjunct mission requirements increase.

Chapter 1

National Missile Defense: The Problem and Solutions

> *The President's tone was soft, sad almost, as he addressed the Deputy Secretary of State. "What is the population of Libya?" "Two million, sir, give or take a hundred thousand…" The President turned down the table toward the Chairman of the Joint Chiefs. "Harry, how many people would we lose if a three megaton device went off in New York?" …The Chairman reflected a moment. "Between four and five million, sir."*
>
> —The Fifth Horseman[1]

> *I believe the proliferation of weapons of mass destruction presents the greatest threat that the world has ever known. We are finding more and more countries who are acquiring technology—not only missile technology—and are developing chemical weapons and biological weapons capabilities to be used in theater and also on a long-range basis. So I think that is perhaps the greatest threat that any of us will face in the coming years.*
>
> —Secretary of Defense William Cohen[2]

The Cold War threat that was characterized by a USSR launch of a large number of ballistic missiles towards the United States has been replaced today by an even less stable ballistic missile security environment. The US National Security Strategy recognizes the existence of threats with both the capability and will to use weapons of mass destruction launched by ballistic missiles. This threat environment coupled with a high leverage to attack ballistic missiles in the boost phase, points to a National Missile Defense (NMD) solution that includes laser weapons.

Four laser architectures have been evaluated as potential boost-phase defenses using NMD technical, operational, fiscal and political criteria. The Space Based Laser (SBL), SBL with Relay Mirrors, Ground Based Laser (GBL) with Relay Mirrors, and Airborne Laser (ABL) with Relay Mirrors each meet the NMD requirements with varying degrees of success. Overall, a Relay Mirror architecture accepting multiple laser sources was found to produce the best NMD boost-phase defense while reducing potential technical, operational, and political issues. The first step in proving this requires discussion of the threats which drive National Missile Defense implementation.

The Threats

Today's National Security Strategy (NSS) recognizes that of the three identified threats to the goals and interests of the United States, Weapons of Mass Destruction (WMD) pose the "greatest potential threat to global security."[3] The NSS also points out that the only military defense against WMD is a "highly effective missile defense,"[4] yet despite this, National Missile Defense (NMD) is only a future possibility. "We are developing missile defense programs that position the US to deploy a credible national missile defense system should a threat materialize."[5] However many of these threats already exist.

In order for a WMD missile threat to be credible, the enemy must have both the *capability* and the *will* to attack the United States with ballistic missiles. Looking at capabilities, the intelligence community's National Intelligence Estimate projected in 1995 that there was very little threat that any developing country could produce a ballistic missile capable of hitting the United States within 15 years.[6] However, this estimate was made with some major exceptions: North Korea, Russia and China.

The North Koreans are currently developing the Taepo Dong 2 missile which the Office of the Secretary of Defense projects will have a operating range of greater than 4000 kilometers.[7] While this range would barely reach the Aleutian island chain in Alaska, it demonstrates that North Korea can strategically attack many of the US bases in Asia with WMD ballistic missiles and is on track to threaten the continental United States. Russia and China already have that capability.

Russia of course, still has available over 3500 nuclear warheads[8] capable of reaching the United States. In a 1995 report to Congress, the Ballistic Missile Defense Organization (BMDO) sited the most serious ballistic missile threat as being a launch of up to 20 WMD warheads by a "wild card" country that has obtained the weapons from the Former Soviet Union.[9] In fact, Russia has offered SS-25s and SS-19s for sale on the international market as launch vehicles for satellites.[10] It doesn't take much imagination to see nuclear warheads attached to these ICBMs again, this time by a rogue WMD power that wishes to threaten the US. A similar story can be told about China.

While China is believed to have more than a dozen ICBMs capable of reaching the US,[11] it is known that China has transferred missile technology to both Iran and Pakistan and exported chemical warfare-related material to Iran.[12] Similarly, these strategic capabilities have also been passed to transnational threats like terrorists or rings of organized crime.[13] Therefore, the United States not only has to be concerned about North Korea, Russia, and China, but also a host of other potential enemies who have been supplied with WMD and ballistic missile technologies. Once these enemies have obtained the capabilities, do they have the will to use them against the US?

A country's will to use any weapon in its possession is situational. In other words, what motivates one power to use WMD is not predictable. It should not be said that since a Mutually Assured Destruction (MAD) policy was good enough to deter the Soviet Union for 40 years, then it should be good enough for any other threat in the world today. "This is not because leaders of proliferant states should be considered relatively more likely to be 'irrational.' Rather, it is because those conditions that can contribute to deterrence, i.e. mutual understanding, close mutual attention, communication, and a mutual unwillingness to risk everything for some transcendent goal, are unlikely to pertain reliably to relations with many potential proliferant countries."[14] Indeed, as evidenced by this comment from Saddam Hussain, several countries (China[15], India[16]) have expressed willingness to use WMD ballistic missiles against the US: "Our missiles cannot reach Washington. If they could reach Washington, we would strike it if the need arose."[17] Henry Kissinger argues that MAD was "barely plausible" with one nuclear opponent and "makes no sense in the multipolar world of proliferating powers."[18]

The bottom line is that if the United States is to be successful in the 21st century, it must be able to deter adversaries possessing WMD ballistic missiles. If not, the threat of use by adversaries will prevent or deter the United States from influencing the course of international events. A third world country need not use the WMD ballistic missiles, but only threaten their use in order to be a viable deterrent to U.S. policy.[19]

With these threats in mind, President Clinton on 14 November 1994, "declared a national emergency with respect to the unusual and extraordinary threat to the national security, foreign policy, and economy of the United States posed by the proliferation of nuclear, biological, and chemical weapons (weapons of mass destruction) and the means of delivering such weapons."[20] While this presidential declaration defines the problem, it does nothing to implement national protection against the threat. The US needs full NMD implementation and the best NMD solutions include laser weapons.

Lasers as a NMD Solution

Lasers (Light Amplification by the Stimulated Emission of Radiation) are devices that utilize energy levels between molecules for the generation of coherent radiation. This radiation can be used for everything from bloodless surgery to applying destructive military power. Appendix A reviews several different laser types being developed by the military. There are two main advantages of using lasers as a part of a NMD solution. The first is speed, the speed of light. "A laser could attack an object 1,000 km away in 3 thousandths of a second, while a high-speed rifle-bullet, for example, would have to be fired 16 minutes before impact with such a distant target."[21] This speed advantage allows attacks against ballistic missiles to be evaluated and a second attack initiated if the first is not successful. This is a big advantage in the situation where a kill must be made. The price of failure is WMD death inflicted upon an unprotected population. The second advantage is that laser defenses are able to attack the ballistic missiles in the boost phase.

The boost-phase is the powered flight of the missile from initial launch to final engine shutdown. While Minuteman and Theater High Altitude Area Defense weapon systems are being evaluated for National Missile Defense solutions, neither of these weapons attack during the boost phase. This flight phase is the best place to attack WMD missiles because:

> Tactically, an attack during the boost phase can destroy missiles carrying chemical or biological agents before any smaller warheads are released. The deadly debris could even fall over enemy territory. Technologically,

> rocket plumes from a missile under power are easier to track than is a warhead in its coast phase. Structurally, too, theater ballistic missiles are quite vulnerable during their boost phase. During the last seconds of powered flight, they commonly endure compressive loads about five times their launch weight.[22]

With the boost-phase being the best place to attack ballistic missiles, a laser boost-phase defense can be a potent addition to any National Missile Defense architecture. The US has been developing high-power lasers to support effective missile defenses. In order to evaluate four possible boost-phase laser systems for NMD, reasonable assessment criteria were first established.

Methodology for Assessment of Laser Options

Each laser architecture is assessed from 4 directions: Technical Capabilities, Operational Considerations, Fiscal Complexities, and Political Ramifications.

Technical Capabilities

The technical capabilities of each laser architecture are examined by evaluating both the architecture's feasibility and effectiveness. Technical feasibility is critical to the assessment, because if the technology cannot be built, then the architecture should not be considered. Therefore major technical issues of each architecture are examined to see if the capability exists to build the architecture. Technical effectiveness is addressed by measuring the architecture's ability to meet National Missile Defense requirements.

The NMD requirement used for evaluation is the ability of the boost-phase architecture to kill up to 20 North Korean Taepo Dong 2 missiles launched simultaneously from anywhere in the world toward a target in the United States. Technically this requires the laser to put 2400 Joules/cm² on each of the 20 missiles during the two minute boost phase period. Appendix B shows how this requirement was developed. To measure effectiveness against this requirement, a simulation was built for each laser concept. This simulation not only helps to measure architectural effectiveness, it also points out operational considerations and potential fiscal complexities.

Operational Considerations

Three critical operational factors are addressed for each laser architecture:

1. Reliability: Is the architecture able to reliably meet NMD requirements?
2. Accessibility: Is the architecture accessible for maintenance or upgrades?
3. Flexibility: Can the laser architecture be easily expanded to handle a larger NMD mission or include adjunct missions? Additional military missions able to be accomplished by these laser architectures are covered in Appendix C.

Fiscal Complexities

Relative fiscal rankings of the laser architectures are produced through an examination of the hardware amounts and the complexity required for their implementation. Dollar amounts were not assigned for each simulated architecture because each of the alternatives are still in the research and development stage and therefore have a wide range of implementation cost projections.

Political Ramifications

The political ramifications of each architecture are examined in light of the Anti-ballistic Missile (ABM) Treaty whose stated purpose is to prevent the implementation of an effective National Missile Defense system.[23] In the long run the United States will have to withdraw from the ABM treaty, because the protection of the US public from WMD ballistic missiles is more important than following a treaty which does not address vital US's threats. However in the interim, since international and domestic opinion is an important factor in US policy decisions, it is likely that the US will attempt to negotiate changes to the treaty rather than simply withdrawing. This section will address features of each laser system which might make them more "Politically Negotiable" within the current ABM Treaty format.

Using these technical, operational, fiscal and political NMD criteria, the following assessment shows that the Space Based Laser (SBL), SBL with Relay Mirrors, Ground Based Laser (GBL) with Relay Mirrors, and Airborne Laser (ABL) with Relay Mirrors each meet boost-phase requirements with varying degrees of success.

Notes

[1] Larry Collins and Dominique LaPierre, *The Fifth Horseman*, (New York: Simon and Schuster, 1980), 48.

[2] William Cohen, *Confirmation Hearing*, Jan 1997, http://www.defenselink.mil/pubs/prolif97/.

[3] *A National Security Strategy for a New Centur*y, (The White House, May 1997), 6.

[4] Ibid., 14.

[5] Ibid., 14.

[6] Robert Braham, et al., "Ballistic Missile Defense: its back," *IEEE Spectrum,* Sept 97, 30.

[7] Office of the Secretary of Defense, *Proliferation: Threat and Response*, (Washington D.C., April 1996), 9.

[8] *Start II Treaty*, http://www.acda.gov/treaties/start2.htm.

[9] Ballistic Missile Defense Organization, USAF. *1995 Report to Congress on Ballistic Missile Defense*, (Washington D.C., September 1995), 3-3.

[10] Angelo M. Codevilla, "Defenseless America," *Commentary*, (Sep 96), 51.

[11] Michael A. Dornheim, et al. "Ballistic Missile Defense: On Target, Part 1," *Aviation Week and Space Technology*, (24 Feb 97), 46.

[12] Office of the Secretary of Defense, 9-10.

[13] *A National Security Strategy for a New Centur*y, 6.

[14] Dr. Kieth Payne, President, *Requirements for Ballistic Missile Defenses*, (Hearing before the Committee on Armed Services, U.S. Senate, January 24, 1995), 19.

[15] Heritage Foundation, *Defending America: Ending America's Vulnerability to Ballistic Missiles*, 15 Mar 96, 6.

[16] Payne, 18.

[17] Brigadier General Alan Johnson, USAF. *Progress to Deployment – The Users Perspective*, USSPACECOM, Peterson AFB, CO. Note: Quoting Saddam Hussain during Desert Storm.

[18] Henry Kissinger, "Ready for Revitalizing," *Washington Post*, (9 March 1995).

[19] Lt Col David K. Barrett, USAF, *National Missile Defense (NMD) Has it's Time Come?*, (US Army War College, Carlsisle Barracks, PA, Jan 1997), 3.

[20] Ibid., 7.

Notes

[21] Office of Technical Assessment, *SDI Technology, Survivability, and Software*, (First Princeton University Press, 1988), 105.

[22] Braham, 40.

[23] *ABM Treaty*, http://www.acda.gov/treaties/abm2.htm.

Chapter 2

Space Based Laser (SBL)

> *SBL offers the potential for a high leverage system to deal with ballistic missiles of virtually all ranges. The SBL appears to be by far the most effective boost-phase intercept system being developed by the Department of Defense.*
>
> —1997 Defense Authorization Act, Committee on Armed Services, United States Senate

In the past, Space Based Lasers (SBLs) have only been the purview of Buck Rogers and Star Trek. Today, it is possible to produce a real SBL that could protect the nation from ballistic missiles. The SBL, as conceived by the Ballistic Missile Defense Organization (BMDO), is a constellation of satellites that would destroy enemy ballistic missiles during their vulnerable boost phase by focusing and maintaining a high powered laser on the target until it achieves catastrophic destruction.[1]

"The core of the space-based laser is a set of cylindrical aluminum nozzles out of which flows a mixture of hydrogen and fluorine. The reaction of these elements produces laser light, which is extracted and shaped into a beam by a set of specialized mirrors. The beam is then focused and stabilized onto distant targets by a large mirror. The kill of a ballistic missile is effected in seconds by heating the structure of the rocket under the beam to its failure point."[2]

As described in Appendix A, the HF laser produced by the SBL fires at a wavelength of 2.7 microns, which cannot penetrate the atmosphere. However the SBL can also be built with a laser that produces HF overtones at 1.3 microns. While this laser is not "eye safe" because it can penetrate the atmosphere, it is more militarily applicable. This HF overtone wavelength allows the SBL to perform adjunct missions discussed in Appendix C that require laser penetration of the earth's atmosphere. In addition, operation of the HF overtone laser allows the SBL to attack ballistic missiles at much lower altitudes, which is critical when time and distance traveled by WMDs are concerned. The Space Based Laser concept sounds novel as a science fiction article, but is the US really in a position today to build such a system?

Technical Capabilities

The USAF BMDO office which manages the SBL effort estimates that a SBL architecture is technologically mature enough to have its first launch as early as 2005.[3] Most of the technical issues that need to be solved prior to production and launch of an SBL demonstrator have been overcome.

Technical Issues

In order to satisfy the NMD requirement for killing 20 Taepo Dong 2 missiles that are launched simultaneously, the SBL designers must solve three major technical issues: High laser power, large adaptable laser optics, and an accurate Acquisition, Tracking, and Pointing (ATP) system.

To meet BMDO's required laser brightness for a SBL, Appendix D shows that the SBL should have on the order of a 5.6 Megawatt (MW) HF overtone laser focussed by a 6 meter primary mirror. To demonstrate that the high laser power is feasible, BMDO operates the Alpha program. Alpha is the HF laser built by BMDO to test the SBL laser concept. BMDO tells us that "in 1991, the Alpha laser demonstrated megawatt class power levels similar to MIRACL [believed to produce 2.2 MW[4]], but in a low pressure, space operation environment."[5] The Chinese believe that the goal of Alpha is to produce a laser with 5 MW output power[6] and if this is true, Alpha is actually proving a laser design of up to 15 Megawatts. This is because the Alpha laser is limited to 1/3 of its available operational length to save on facility costs, thus when the full scale operational device is obtained by adding more rings to the gain generator, it would produce three times the power.[7] While the Alpha only produces 2.2 – 5 MW of power today, it is actually proving out a laser that produces 6.6 – 15 MW. Additionally, optimization of the lasing wavelength to produce HF overtones has proven to have a 65% efficiency in low power lasers.[8] If this can be achieved at high laser powers, the Alpha will have proven HF overtone lasers in the range of 5 – 9.8 MW. With these levels of laser power, the Space Based Laser would not have a power problem.

Similarly, the large optics concerns for SBL have been demonstrated through the Large Advanced Mirror Program (LAMP) program. BMDO used the LAMP program to: "build a lightweight, segmented 4 m diameter mirror which was tested in 1989. Tests verified that the surface optical figure and quality desired were achieved, and that the mirror was controlled to the required tolerances by adaptive optics adjustments. This LAMP segmented design is applicable to 10 meter class mirrors, and the Large Optical Segment (LOS) program has since produced a single mirror segment sized for an 11 meter mirror."[9] The LAMP and LOS optical risk reduction programs show that the SBL primary mirrors are realizable in the near future.

The last technical concern with the SBL concept, the ATP system, has also had its risk reduced through a series of experiments. The space-borne Relay Mirror Experiment, relayed a low-power laser beam from a ground site to low-earth orbit and back down to a scoring target board at another location with greater pointing accuracy and beam stability than needed by SBL. In 1998, the Phillips-Laboratory-executed High Altitude Balloon Experiment, will demonstrate autonomous end-to-end operation of the key ATP-Fire Control functions in a realistic timeline against actual thrusting ballistic missiles."[10]

To complete the testing of SBL's three critical technology areas, BMDO integrated the Alpha laser with LAMP's 4 meter mirror and the beam control system. This Alpha-LAMP Integrator (ALI) has been conducting high power tests since 20 February 1997.[11] Overall, while most of the critical SBL technology concerns have been solved on the ground, the real challenge will be to integrate these technologies and actually conduct operations in space. In order to fully prove that the SBL can do this, BMDO has proposed to build and launch Starlite, a SBL demonstration satellite which would be the first step to a Space Based Laser operational constellation.

Possible Operational Constellation

An operational SBL constellation would be similar to the one developed in Appendix D and shown in Figure 1. These calculations and simulations show that a 24 SBL satellite constellation can kill 20 Taepo Dong 2 missiles launched anywhere in the world at anytime. Figure 1 shows the SBL constellation with 4 polar orbits containing 6 SBL satellites at 1200 kilometers altitude. The figure also shows two SBLs having simultaneous killing power on a simulated ballistic WMD launch. To accomplish this at a maximum range of 4082 kilometers, each SBL has a 5.6 MW HF overtone laser focused by a 6 meter primary mirror. Despite the technological capabilities of the SBL concept, there are operational concerns which might make other laser options more attractive for NMD boost-phase operations.

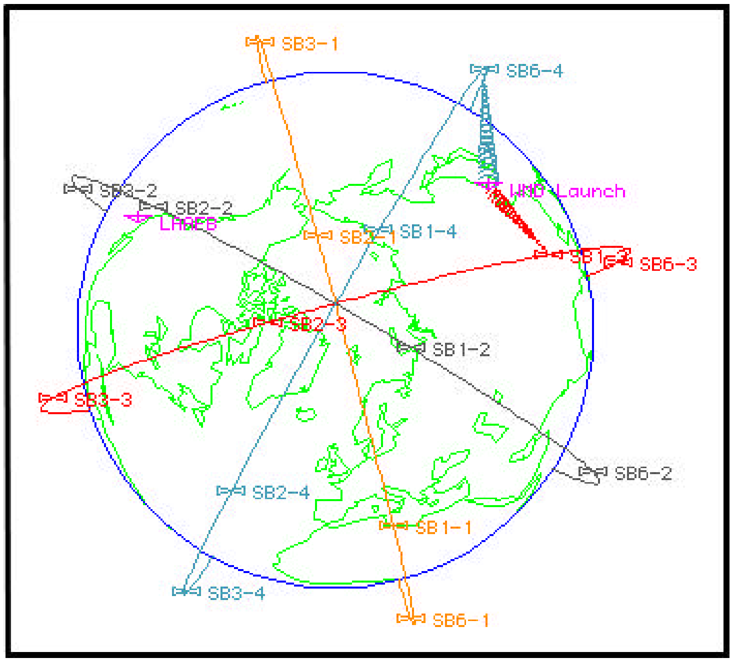

Figure 1. SBL Constellation

Operational Considerations

The SBL concept has unresolved reliability, accessibility, and flexibility issues. In terms of reliability, the SBL satellites will be state-of-the-art laser systems that are required to correctly operate in space the first time and every time. Even with the Starlite demonstrator to work out potential reliability issues, SBL constellation reliability without constant testing and component modification, will always be a concern.

SBL's inaccessibility also severely impacts required Operations and Maintenance (O&M) activities. In OTA's SBL evaluation, it was stated that: "The status of dormant space assets would have to be monitored carefully and frequently. Once defective space systems were diagnosed, they would have to be repaired or replaced. The system architecture would have to incorporate some combination of redundancy or on-orbit repair or replacement to maintain the total system."[12] Additionally, when a SBL satellite uses all of its laser combustion fuel, the satellite is either wasted or it must be refueled. SBL's inaccessibility in space makes these O&M operations difficult and expensive.

Flexibility is also an operational issue with the SBL architecture. In order to upgrade this system, each SBL satellite would have to be replaced with an improved version, which makes it expensive for SBL to incorporate new requirements. The bottom line is that SBL's inaccessibility causes it to perform poorly against all operational criteria.

Fiscal Complexities

From a fiscal standpoint, the only point to be made is that each SBL is likely to be an expensive proposition. Each SBL satellite is projected by BMDO to weigh 17,500 kilograms.[13] Using the Aerospace Corporation's historical cost verses weight information, which shows that satellites average cost is roughly $50,000 per pound,[14] the first satellite in this constellation would approach $2 billion dollars. The remaining SBLs are likely to be lower in cost, but still very expensive.

Political Ramifications

Regarding ABM Treaty issues, SBL is probably the most volatile of the NMD laser alternatives. Not only does SBL ignore the intent of the treaty, it also places the ABM weapons in space. This has been prohibited by both the ABM Treaty and the recent ABM Helsinki Agreement between Presidents Clinton and Yeltsin. The only argument that mitigates this is that the ABM treaty does not apply to the technologies inherent in SBL. Since the ABM treaty only requires discussions (and not limitations) of ABM architectures “based on other physical principles,” [15] SBL could slip through a treaty loophole. On the other hand, while not ratified, the Helsinki agreement specifically rejects space-based ABM components.[16] Politically, SBL is a ABM Treaty “hot potato.”

As a final summary, a SBL boost-phase architecture can be implemented which meets all NMD requirements. The constellation, based on current risk reduction projects, is technically achievable on the ground, but risky for operations in space. Additionally, the SBL architecture has operational, fiscal, and political issues that might be improved upon by other NMD laser alternatives.

Notes

1 Space and Missles Systems Center USAF, *Space Based Laser – Project Background*, http://www.afbmd.laafb.af.mil/ade/backgrnd.htm.

2 Vance T. Coffman, et al. Letter to the Honorable Strom Thurmond,15 March 1995.

3 Colonel Loverro, *Space Based Laser Readiness Demonstrator*, Briefing for USAF SMC/AD, (9 Dec 97).

4 Yang Peigen, “Progress in Chemical HF/DF Lasers”, Jiguang Jishu: *Laser Technology*, (Vol 12, No. 3, Translated by Leo Kanner Associates for the National Air Intelligence Center, June 1988), 7.

5 Space and Missles Systems Center USAF.

6 Peigen, 7.

7 D. Wildt, and S. Lissit, *Space-Based Chemical Lasers for Ballistic Missile Defense*, (AIAA 24th Plasmadynamics & Lasers Conference, Orlando FL, July 93), 5.

8 Ibid., 6.

9 Space and Missles Systems Center USAF.

10 Ibid.

11 J.A. Horkovich and P.J. Pomphrey, *Recent Advances in the Alpha High Power Chemical Laser Program*, (28th Plasmadynamics and Lasers Conference, Atlanta, GA, June 97), 7.

12 Office of Technical Assessment, *SDI Technology, Survivability, and Software*, (First Princeton University Press, 1988), 166.

13 Space and Missles Systems Center USAF.

14 Aerospace Corporation, *Satellite Cost Vs. Weight*, (Whitehair Presentation, 1997).

15 *ABM Treaty*, http://www.acda.gov/treaties/abm2.htm.

16 *Helsinki Agreement*, Clinton-Yeltsin Summit at Helsinki, (21 Mar 98), http://www.usis.fi/whatshap/summit27.htm.

Chapter 3

SBL with Relay Mirrors

> *For SBL, fighting [relay] mirrors that relay the energy to the target give the SBL concept a more robust capability in terms of survivability, tolerance to device jitter and lower throw weight in LEO.*
>
> —L. Sher in "Optical Concepts for Space Relay Mirrors"[1]

The SBL with Relay Mirrors is one concept that has the capability to improve on the SBL NMD architecture. This architecture uses only a few SBLs which fire their laser energy to the relay mirrors in low-earth orbit. These relay mirrors then refocus the laser energy on the ballistic missile targets anywhere over or on the earth. This arrangement allows the SBL with Relay Mirror architecture to perform all the same NMD and adjunct missions as the SBL architecture. However since the Relay Mirrors are less expensive than the SBL satellites, the total architecture cost is cheaper. The SBL with Relay Mirrors concept is not only cheaper, it is more survivable and has roughly the same technical maturity as the SBL concept.

Technical Capabilities

While AF/BMDO has not specifically pursued detailed relay demonstrations, the relay technologies are mature because many of the issues are inherent in the SBL program. The satellite technologies are mature enough for AF/BMDO to propose a first launch of SBLs in 2005 followed by relay mirror satellites in 2008.[2]

Technical Issues

In addition to the SBL technical issues discussed earlier, the relay mirrors have at least one major technical hurdle of their own, while alleviating a potential SBL ATP problem. One might believe that the major technical issue for the Relay Mirrors is that the bifocal relay mirror design requires two large mirrors (Appendix E calculates a 6 meter and 7.3 meter diameters for this design) that are error free to 0.13 microns (operational wavelength divided by ten).[3] However LAMP and LOS risk reduction programs have shown that these mirrors can be built. Additionally, this issue is similar to the one encountered by the Next Generation Space Telescope (NGST). NASA has found contractor teams confident that they would be ready to launch their NGST designs, some with optical elements up to 8 meters in diameter, by 2005.[4] The biggest technical hurdle of the relay satellites is not the large relay mirrors, but the small ones.

These smaller mirrors are responsible for turning and shaping the laser beam within the bifocal relay satellites.[5] They must do this while having the entire energy of the megawatt lasers focussed onto a much smaller area than on the larger relay mirrors. As an example, if the transmit mirror (6.0 meter diameter) focuses a 5.6 MW laser, the mirror will be exposed to an average of 200 kilowatts per square meter on its surface. However, a turning mirror within the relay satellite, which may be only 1 meter in diameter (or smaller), would see an average of 7200 kilowatts per square meter – an increase of 3600%! Yet the mirror coatings and the mirror must survive and work perfectly every time. One small error in design, manufacture or operations could be a big disaster given those power levels.

Yet this is exactly the environment that the mirrors within the Alpha laser already operate. In fact during the ALI experiments, two uncooled silicon mirrors were used in the full power Alpha beam train. The mirrors reportedly performed well during full power Alpha laser tests with no visible signs of damage.[6] With this relay technical hurdle solved by SBL testing, can the Relay concept help solve SBL technical issues?

As discussed earlier, one of the major SBL requirements was the correct operation of the Acquisition, Tracking, and Pointing subsystem. Obviously, this system's operation would be complicated by laser induced jitter within the satellite, similar to what was seen during the Alpha-LAMP integration program. "An effort was taken to identify and resolve jitter issues in the ALI subsystems. An vibration isolation system was installed to reduce the far field (target) jitter by as much as 50 percent."[7] But if relay mirrors are used, they also act as a vibration isolation system for the laser. Since the receive aperture of the relay mirror is only sized to capture the Airy disc of the transmitted laser (See Appendix E), a spatial filtering is performed on the laser and high frequency jitter is removed. This increases the loss of the transmitted beam, but it also simplifies operation of the ATP system by stabilizing the laser.[8] With the technical issues of the SBL with Relay Mirrors architecture rapidly being solved by BMDO, what would an operational constellation look like?

Possible Operational Constellation

An operational SBL with Relay Mirror architecture would be similar to the one developed in Appendix E and shown in Figure 2. Three SBL satellites that provide the firepower for the constellation are in an equatorial orbit at an altitude of 5200 kilometers. This altitude allows every Relay Mirror to be in view of at least one, and fifty percent of the time two, Space Based Lasers. The SBL satellite design is similar to the designed for the SBL only constellation, except that this SBL contains a 6.8 MW HF overtone laser.

The required laser power was increased by twenty percent to overcome losses in the relay laser link. The SBL has a 6 meter primary mirror that focuses the laser and which requires a 7.3 meter receive mirror on the relay satellite. In optimizing the final design for system cost, it could prove less expensive to produce a larger SBL primary mirror and reduce each of the Relay Mirror's receive apertures.

The bifocal relay mirror satellites were placed in the same orbits as the SBL satellites discussed in the SBL only constellation. These relay mirrors receive the laser shot from a SBL with their 7.3 meter mirror and refocus and retransmit the laser with the 6 meter mirror. This gives the same killing range of 4082 kilometers and worldwide access as the SBLs in the previous chapter.

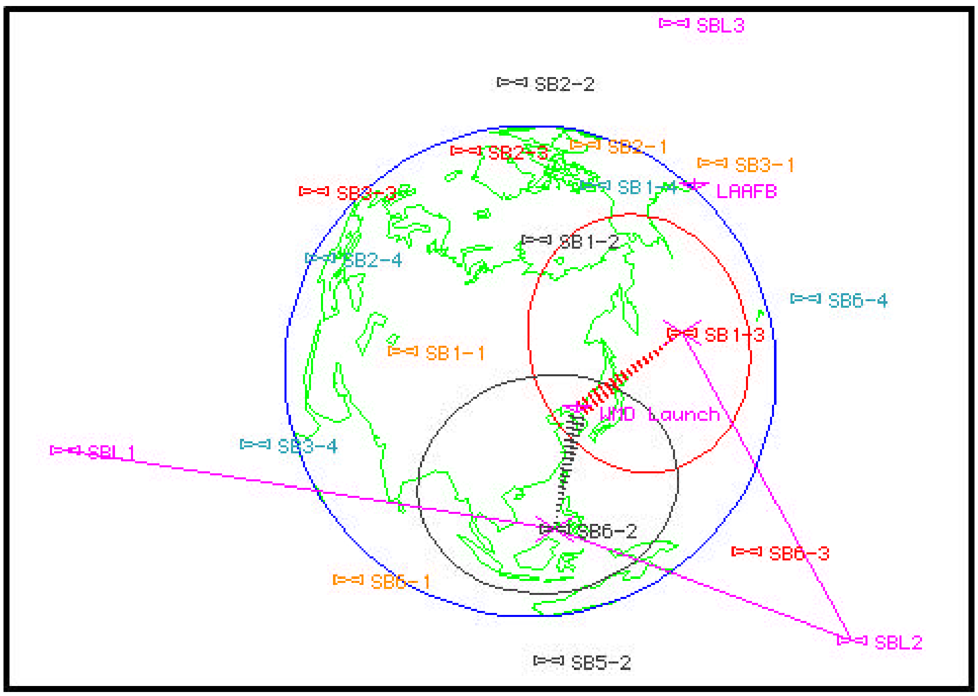

Figure 2. SBL with Relay Mirrors Against a Ballistic Missile Launch

Figure 2 shows the SBL with Relay Mirrors constellation as it simulates an attack against a North Korean ballistic missile launch. In this particular scenario, two Relay Mirrors (SB1-3 and SB6-2) have views of the missile launch and individually have the capabilities to kill all 20 ballistic missiles. Relay Mirror SB6-2 can be fed laser energy by SBL1, while SBL2 can feed either Relay Mirror SB6-2 or SB1-3. This simulation and the calculations in Appendix E show that this architecture meets all the NMD requirements.

Operational Considerations

The SBL with Relay Mirrors concept has minor operational benefits over the SBL only constellation. One positive reliability aspect is that the orbital position of the SBL satellites in this architecture make them a little less vulnerable to enemy offensive attacks. Since the SBLs are at higher altitudes, they are harder to reach by enemy offensive weapons and their lower inclination orbits minimize direct threats from Russian antisatellite laser threats.[9] Additionally, from an accessibility standpoint, while the SBLs still require laser fuel to be delivered to space, only three satellites need refueling to resupply the entire architecture. While SBL with Relay Mirrors has only minor operational advantages over SBL, it also has significant cost incentives.

Fiscal Complexities

The Relay Mirrors in this concept have been estimated to weigh 20% less than the SBLs they replace (from the SBL only architecture).[10] Using the Aerospace Corporation's cost information,[11] this translates to a 20% cost savings on each satellite. This correlates well with BMDO's cost estimates which have priced the initial Relay Mirror readiness demonstrator as 25% cheaper than the SBL demonstrator.[12] With each relay mirror costing only 75% of an SBL satellite, the total cost savings for the entire architecture, including the 3 required SBLs, are still 13% $\{[(.75 \times 24) + 3]/24\}$over the

SBL constellation. This means that billions of dollars could be saved by implementing SBL with Relay Mirrors over the SBL only design; a significant cost advantage.

Political Ramifications

Politically, the SBL with Relay Mirror architecture improves little over the SBL architecture. The only minor advantage is that there are only 3 actual laser weapons in space as opposed to 24. While this would probably have little effect on the ABM treaty negotiations, it could matter with public opinion.

As discussed, a NMD boost-phase defense built on SBLs with Relay Mirrors is technically sound, but just as technically risky, as the SBL only design. The concept can meet the NMD requirements and does have significant cost savings over the SBL architecture. However because it only shows minimal operational and political improvements over the SBL architecture, there are still significant issues that might be improved upon by other laser alternatives.

Notes

[1] Lawrence Sher, *Optical Concepts for Space Relay Mirrors*, (Phillips Laboratory, NM), 1.

[2] Colonel Loverrro, *Space Based Laser The Path Ahead*, Briefing for USAF SMC/AD, (17 Dec 97), 14.

[3] Office of Technical Assessment. *Ballistic Missile Defense Technologies*, (U.S. Government Printing Office, 1985), 148.

[4] H.S. Stockman, *The Next Generation Space Telescope*, (Space Telescope Science Institute, June 97), ix.

[5] Lawrence Sher, *Space Relay Mirrors*, Briefing to Air War College, (Phillips Laboratory, NM, 23 Sept 97).

[6] J.A. Horkovich and P.J. Pomphrey. "Recent Advances in the Alpha High Power Chemical Laser Program," (28th Plasmadynamics and Lasers Conference, Atlanta, GA, June 97), 6.

[7] Ibid., 6.

[8] Sher, *Optical Concepts for Space Relay Mirrors*, 4.

[9] Lawrence Sher and USAF Captain Stephen Mcnamara, "Relay Mirrors for Space Based Lasers," *Laser Digest*, (Air Force Weapons Laboratory), Note: to be published.

[10] Lawrence Sher, "Relay Mirrors for Space Based Lasers," Fig 1.

Notes

[11] Aerospace Corporation, *Satellite Cost Vs. Weight*, (Whitehair Presentation, 1997).
[12] Loverro, 15.

Chapter 4

Ground Based Laser (GBL) with Relay Mirrors

GBLs with Relay Mirrors in space offer a virtually infinite magazine [for NMD]

—L. Sher in "Space Relay Mirrors" briefing to Air War College[1]

The GBL with Relay Mirror architecture consists of several ground-based laser sites that fire a high-energy laser to relay satellites in low-earth orbit. These relay mirrors then refocus the laser on the ballistic missile targets and destroy them. The GBL sites would have adaptive optics to correct for atmospheric distortions and would fire either a HF overtone or a COIL laser (See Appendix A for laser type definitions) which have good atmospheric transmission. Even though, "it would take several GBL laser sites to assure clear weather at one site all the time,"[2] once the lasers could fire, they would be fed with a very "deep magazine."[3] The ground basing of the laser source brings not only operational benefits, but technical challenges.

Technical Capabilities

The USAF BMDO office estimates that a Relay architecture is technologically mature enough to have its first launch as early as 2008.[4] However that timeline does not include the high energy Ground Based Lasers in this architecture. This ground basing of the laser source will bring additional technical challenges to AF/BMDO.

Technical Issues

In order for the GBL to supply enough laser power to satisfy NMD requirements, the laser must overcome atmospheric and architecture losses. The GBL generated laser beam is affected by three different atmospheric phenomena during its propagation to the relay mirrors: transmission, turbulence and blooming. Atmospheric transmission is governed by the laser wavelength. Since the GBL will be lasing at 1.3 microns, this is not a concern because atmospheric transmission is nearly 100%. The real issues come from turbulence and blooming.

Atmospheric turbulence occurs because variations in temperature, pressure, and humidity lead to random variations in the atmosphere's index of refraction as seen by the propagating laser beam. Left uncorrected, turbulence would cause the laser beam to bend and diverge two or three orders of magnitude beyond its diffraction limit.[5] Atmospheric blooming occurs when the laser energy is absorbed by water droplets in the atmosphere. As the energy is absorbed by the aerosols, the heated air expands radially outward and causes the air index of diffraction to change along the beam's radius. This creates a lensing effect which spreads the laser beam much more than what is predicted.[6] Both turbulence and blooming can substantially reduce the received laser power if they are not corrected for by using adaptive optics. Thus adaptive optics is the first GBL technical challenge.

The adaptive optical system is required to sense atmospheric distortions in real time using a cooperative beacon on the relay satellite and sensors on the ground. The adaptive optics must then use actuators that continuously change the shape of the laser beam-director mirror to cancel wave-front errors introduced by the turbulence and blooming.[7] While "the efficacy of these systems has been demonstrated for ground-based (GBL) systems,"[8] they are complex. The adaptive optics might require adjustments every .002 seconds[9] using actuators operating every 5 centimeters[10] across a mirror modifying a high energy laser. After being modified by the adaptive optics to minimize atmospheric losses, the laser must pass through the atmosphere and also overcome architectural losses. These losses are accumulated as the laser passes through each relay satellite and finally to the target. This means that the laser must be powerful enough to overcome these losses and still meet the NMD requirements.

To complete the requirements and kill all 20 missiles within two minutes, Appendix F shows that the GBL must be able to produce a minimum power of 15.7 MW. Today, it is believed that the MIRACL laser at the U.S. Army's High-Energy Laser Systems Test Facility at the White Sands Missile Range can produce a DF laser output of 2.2 MW.[11] MIRACL has also helped validate laser concepts that show that chemical laser devices can be scaled up by 38-fold, proportionately. In other words, it is possible to develop a chemical laser device with 80MW as the output power.[12] As an additional validation, the Alpha laser can scale up by a factor of 3, to somewhere between 6.6 – 15 MW. Production of a ground based 16 Megawatt system should not be a major issue. However, particular attention will have to be paid to potentially critical atmospheric propagation and adaptive optics issues.

Possible Operational Constellation

An operational GBL with Relay Mirror architecture would be similar to the one developed in Appendix F and shown in Figure 3. The constellation consists of three GBL sites separated by 1000 kilometers to provide a 97% chance that one will have clear weather when required. The GBLs are able to fire and track on low-earth orbit relay satellites and have incorporated adaptive optics correcting for turbulence and blooming. The GBL transmit mirrors are 4 meters in diameter and fire a 1.3 micron laser with minimum power of 15.7 Megawatts. The GBL architecture also contains 24 relay mirrors in 4 polar orbits at an altitude of 1200 kilometers similar to the SBL relay constellation. Each relay has a 4.0 meter receive mirror whose size is driven by the relay satellite separation. The 6.0 meter relay transmit aperture size enables the relay mirror to eliminate 20 ballistic missiles at the maximum killing range of 4,082 kilometers.

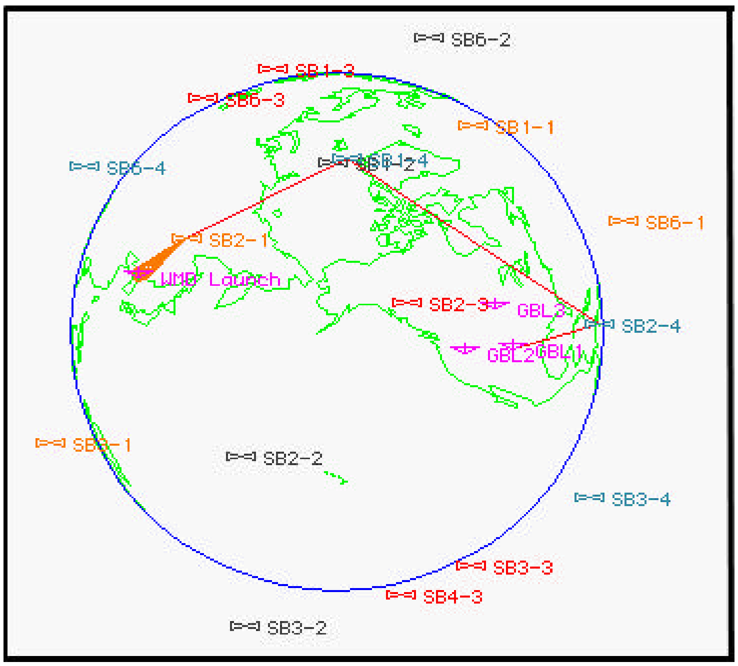

Figure 3. GBL with Relay Mirrors Attacking Ballistic Missile Launch

All of these pieces come together to build a GBL with Relay Mirror architecture that can satisfy the NMD requirements. It can kill 20 Taepo Dong 2 missiles launched anywhere at anytime… as long as the weather is clear at one of the 3 GBL sites. This is demonstrated in Figure 3 where GBL 1 has clear weather and focuses on the relay mirror (SB2-4) that is currently overhead. This relay passes the laser to relay mirrors SB1-2 and then to SB2-1 which then destroys the ballistic missiles.

Operational Considerations

The GBL concept has significant operational advantages over the previous laser options, but also one drawback. Reliability, accessibility, and flexibility are all improved over the SBL concepts because of the ground laser source. The drawback is possible prevention of laser firing due to bad weather.

Because the high energy laser is the most complicated subsystem in any of the laser architectures, the system reliability will be improved by putting the laser in reach of constant human attention. This accessibility enables maintenance and operational improvements that could not be implemented if the laser source is in space. Unfortunately, the system reliability is also affected by the limited availability of GBL firing due to weather.

As discussed in Appendix F, the three GBL sites were provided to roughly equal an assumed 97% availability of SBL satellites. Unfortunately, even if the two laser sources are designed to have the same technical availability, the GBLs still have the inherent disadvantage of the enemy knowing when the lasers cannot fire. When the SBLs are not available, US enemies would not normally know and thus the boost-phase defense still has deterrent value. When the GBL sites are clouded over, anyone with a weather hyperlink knows that the GBLs are no longer are able to provide protection. Thus while the GBL architecture provides the better technical reliability because of its ground laser source, its deterrent value is not as great as that of the SBL architectures. This may be a minor drawback for a boost-phase defense which is only part of the total NMD architecture, but it is a drawback.

Laser accessibility also benefits the operational flexibility of the GBL architecture. The first benefit is what BMDO calls the "Deep Magazine,"[13] which simply means that the GBL firing time is only limited by the combustible fuel on site. This is a real benefit if there are more targets than originally believed. Additionally, if adjunct missions such as those discussed in Appendix C are approved, this "deep magazine" can be used or the accessible GBL can be made brighter to accommodate them. Overall, the GBL with Relay Mirrors architecture has significant operational advantages over the SBL concepts primarily related to its accessibility for fuel and modifications. The only issue which mars this is GBL's reduced deterrence value due to weather intervention.

Fiscal Complexities

The GBL with Relay Mirrors architecture is comparable in cost to the SBL with Relay Mirrors architecture. Each have 24 satellite relay mirrors in low earth orbit to do the attack mission. The GBL relays do have smaller receive mirrors (4.0 meters compared to 7.3 meters for SBL), and this could be significant since mirror production time is proportional to the cube of the mirror diameter.[14] This mean's that the SBL relay's receive mirrors take six times longer to manufacture than GBL's counterpart and thus the GBL relay constellation is less expensive. However, the real fiscal question comes down to which of the laser sources are more expensive. The earlier SBL analysis showed that the SBLs would cost on the order of two billion dollars each. Even if the GBL sites cost this much, it is hard to believe that the GBL operations and maintenance activities would be as expensive as the SBL launches, operations and on-orbit maintenance. Despite this, a recent BMDO analysis shows that the SBL concept has a slight cost edge over the GBL concept.[15]

Political Ramifications

Regarding the ABM Treaty, there are two political advantages for the GBL with Relay Mirror architecture. The first is that while there are three GBL sites, where only one is allowed in North Dakota by the ABM Treaty, it might be negotiable point since the sites are "based on other physical principles" which only require treaty discussions.[16] The second advantage is that the GBL concept places no actual weapons in space. While the Helsinki agreement prohibits any ABM components (like relay mirrors) resident in space,[17] having no weapons there may make a difference in the eyes of the international community when ABM renegotiations take place.

An NMD architecture built on GBLs with Relay Mirrors is technically sound and can meet all of the NMD requirements. It is cost comparable to the SBL with Relay Mirror architecture, however it does have significant operational advantages because its laser source is accessible. This accessibility provides future flexibility and a "deep magazine" which are key advantages, unless of course the skies are cloudy. This cloud issue could be solved by the ABL NMD architecture

Notes

[1] Lawrence Sher, *Space Relay Mirrors*, Briefing to Air War College, (Phillips Laboratory, NM, 23 Sept 97).

[2] Office of Technical Assessment, *SDI Technology, Survivability, and Software*, (First Princeton University Press, 1988), 123.

[3] Colonel Loverrro, *Space Based Laser The Path Ahead*, Briefing for USAF SMC/AD, (17 Dec 97), 19..

[4] Colonel Loverrro, *Space Based Laser Readiness Demonstrator*, Briefing for USAF SMC/AD, (9 Dec 97), 14.

[5] American Physical Society, *Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons*, (New York, 1987), 188.

[6] Robert Braham, et al., "Ballistic Missile Defense: its back," *IEEE Spectrum*, (Sept 97), 45.

[7] American Physical Society, 123.

Notes

[8] L.D. Weaver and R.R Butts, *ABLEX: High Altitude Laser Propagation Experiment*, (Phillips Laboratory, Kirtland AFB, NM, Aug 1994), 2.

[9] Braham, 43.

[10] R. K. Tyson, et al, *Adaptive Optics System Considerations for Ground-to-Space Propigation*, (SPIE Vol 1221, Propagation of High-Energy Laser Beams Through the Earth's Atmosphere, 1990), 150.

[11] Yang Peigen, "Progress in Chemical HF/DF Lasers", Jiguang Jishu: *Laser Technology*, (Vol 12, No. 3, Translated by Leo Kanner Associates for the National Air Intelligence Center, June 1988), 5.

[12] Ibid., 5.

[13] Loverrro, *Space Based Laser The Path Ahead*, 19.

[14] American Physical Society, 179.

[15] Loverro, *Space Based Laser Readiness Demonstrator*, 56.

[16] *ABM Treaty*, http://www.acda.gov/treaties/abm2.htm.

[17] Helsinki Agreement, Clinton-Yeltsin Summit at Helsinki, (21 Mar 98), http://www.usis.fi/whatshap/summit27.htm.

Chapter 5

Airborne Laser (ABL) with Relay Mirrors

> *Some have called the Airborne Laser the most revolutionary advance in warfighting technology in 40 years. The potential of a silent, very long range, speed-of-light weapon in the theater air defense environment is staggering*
>
> —Dr. Sheila Widnall, Secretary of the Air Force

The Air Force's Airborne Laser is currently being designed for boost-phase negation of enemy missiles in a US military theater of operations. This 1.3 micron COIL laser[1] (see Appendix A) flying on a modified 747 aircraft will provide Theater Missile Defense (TMD) at ranges of up to 600 kilometers. The Airborne Laser could also provide up to 200 seconds of laser power[2] for a National Missile Defense architecture. The ABL would fire its laser up to a low-earth orbit relay satellite constellation which would pass the laser around the earth to kill the enemy ballistic missiles. While the ABL boost-phase defense is only able to kill 14 of the 20 NMD ballistic missiles, it is the simplest of the NMD boost-phase architectures. This is because ABL is not inhibited by bad weather and is already scheduled to demonstrate a theater missile shootdown in 2002.[3] Only the space based relay mirror constellation is required to make this concept a future reality.

Technical Capabilities

The ABL architecture's technical issues are a combination of the difficulties discussed for the SBL and GBL concepts, plus a significant relay mirror challenge.

Technical Issues

The ABL technical issues are similar to SBL in the sense that a powerful laser must be built light enough to fly and similar to GBL because its laser has to fire through the atmosphere. Since the ABL was designed for theater ballistic missiles and ranges of up to only 600km, it is being built with a 3 MW[4] COIL laser and at best a 2 meter (some sources say 1.5 meter) diameter transmit aperture.[5] Additionally, the ABL contains the adaptive optics required by the GBL architecture since the laser must fire through the atmosphere, and the ATP hardware of the SBL design to track either ballistic missiles or relay satellites. This is an aggressive amount of hardware to fly, even on a 747. However ABL's low laser power (which meets mission requirements for Theater Missile Defense) creates problems in trying to meet the National Missile Defense requirements.

As discussed in Appendix G, by the time the ABL produced laser is ready to be focussed on target, it's power has been reduced to 37% of its original 3MW by architecture and atmospheric losses. This requires that the relay mirror transmit optics be increased in size to achieve the required laser fluence on the target. BMDO's Large Optical Segment program has demonstrated optics up to 11 meters in diameter[6] and when the relay mirror constellation uses these, the ABL with Relay Mirror architecture can kill 14 ballistic missiles at maximum range in the allocated two minutes. Eleven meters is an exceptionally large aperture to have on a bifocal relay mirror and a driving technical challenge, but given that this and ABL weight issues can be overcome, ABL can perform a National Missile Defense mission.

Possible Operational Constellation

An ABL boost-phase NMD architecture would be similar to the one developed in Appendix G and shown in Figure 4. The architecture consists of a single ABL orbiting in the United States and a 24 satellite relay mirror constellation in low-earth orbit. The relay satellites have the same orbital parameters as the SBL and GBL concepts, with the only difference being in the relay optics sizes. The ABL's small transmit optics drive the relay receive optics to increase to 6.5 meters in diameter and ABL's low laser power requires the relay transmit optics to grow to an aggressive 11 meters. This ABL and Relay Mirror architecture is simulated in Figure 4 and can kill 14 of the 20 possible enemy ballistic missiles at maximum range. While this does not meet the NMD requirement, it does reduce the target load for the rest of the NMD architecture.

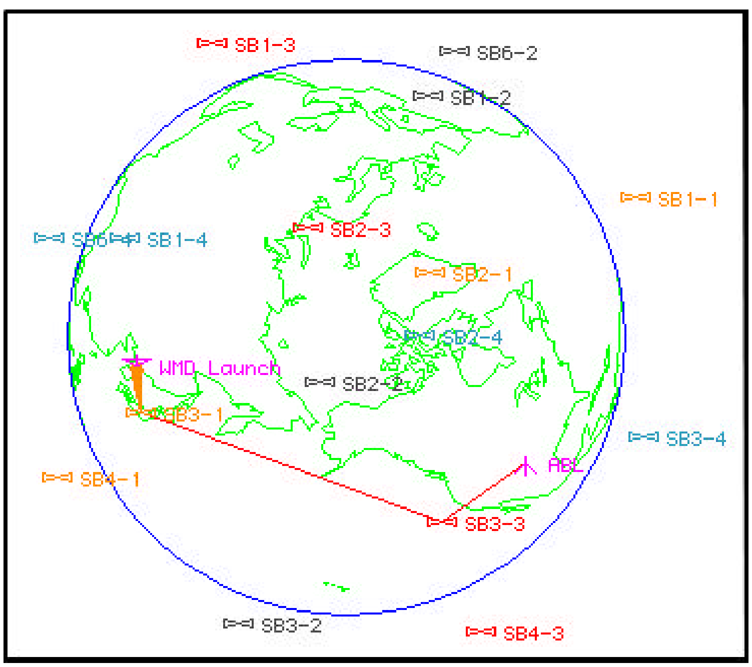

Figure 4. ABL with Relay Mirrors Attacking WMD Launch

Operational Considerations

From an operational viewpoint, the ABL with Relay Mirrors NMD concept is the best of the concepts. It has all the reliability and accessibility benefits of the GBL with Relay Mirror architecture and the additional benefit of not having to consider weather interference. This is because the ABL's cruising altitude of 12.9 km is above the tropopause or the well-established height below which clouds usually occur in most latitudes.[7] It could be argued that since the ABL is flying, it is not as accessible as GBL. However, the counter argument is that any ABL problem could be solved by scrambling a second ABL, while issues with the first one are corrected on the ground. Because the operational benefits allow a single ABL to be used as NMD's boost-phase defense, this has direct fiscal benefits.

Fiscal Complexities

Fiscally the single ABL laser source is much cheaper than either three GBL or three SBL laser sources. The offset to this savings is that ABL's relay mirrors are much more expensive than the other relay constellations. Using criteria established by the American Physical Society,[8] the large relay mirrors (11 meters vice 4 meters in diameter for GBL) will take 11 times longer to produce than their GBL counterparts and will certainly drive up relay costs. However since laser sources are so expensive (estimated at two billion dollars for a SBL in Chapter 2), the fiscal advantages of the ABL with Relay Mirrors are concluded to offset its disadvantages. Thus, while the relay mirrors are much more complicated than the other architectures due to their 11 meter apertures, it is not obvious that this technologically aggressive issue would cost more than 3 ground or space based laser sources.

Political Ramifications

Politically, the Airborne Laser with Relay Mirror Architecture is the best of all the architectures. It is a National Missile Defense architecture, but its laser source has been approved by the recent Helsinki Agreement[9] for Theater Missile Defense and it is "based on other physical principals"[10] which opens the architecture up for ABM Treaty discussions. Additionally this architecture has political benefits because it places no weapons in space and can be sold as a gradually expanding TMD system that grows into an NMD architecture. Politically a National Missile Defense success.

Overall the ABL with Relay Mirror concept is very powerful. While the transmit relay mirror is technically aggressive and the architecture can only kill 14 of the required 20 ballistic missiles, the concept is potentially cheaper, has the most operational advantages, and is politically the best of the laser alternatives.

Notes

[1] Office of Naval Research, *Chapter X – Weapons, Defense Technology Area Plan*, http://www.dtap.com.

[2] Robert Braham, et al., "Ballistic Missile Defense: its back," *IEEE Spectrum*, (Sept 97), 46.

[3] Ibid., 54.

[4] Ibid., 43.

[5] L.D. Weaver and R.R Butts, *ABLEX: High Altitude Laser Propagation Experiment*, (Phillips Laboratory, Kirtland AFB, NM, Aug 1994), 16.

[6] Space and Missles Systems Center USAF, *Space Based Laser – Project Background*, http://www.afbmd.laafb.af.mil/ade/backgrnd.htm.

[7] Braham, 45.

[8] American Physical Society, *Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons*, (New York, 1987), 179.

[9] Helsinki Agreement.

[10] *ABM Treaty*, http://www.acda.gov/treaties/abm2.htm, Signed 26 May 1972, Ratified 3 August 1972.

Chapter 6

Assessment Summary

> *I have a fundamental requirement for a [NMD] system—be operational and do its job. The biggest mistake we, as a nation, could make is to deploy a system that's not [effective]. The public wouldn't stand for it, and—as the CINC—I would certainly be remiss in my duties, if I let that happen."*
>
> —General Estes, CINC, USSPACECOM[1]

Each of the different laser boost-phase architectures have individual benefits and handicaps which are reviewed in each assessment area. In the end, it is possible to combine the architectures with the result of achieving maximum National Missile Defense benefit without individual architecture handicaps.

Technical Capabilities

In evaluating the technical feasibility of the laser architectures, it has been shown that some of the boost-phase systems are less risky than others. The GBL with Relays has the least technology risk by having proven out most of required laser and adaptive optics technologies while having the smallest relay mirrors. The SBL architectures are more technologically aggressive, primarily due to the challenging high energy lasers which must operate in a space environment. This concern may be mitigated by the proposed Starlite demonstration program. Finally the feasibility of the ABL with Relays is the most questionable, due primarily to the large technically aggressive eleven meter relay mirror which corrects for the low power of the Airborne Laser. This architecture requires 83% more mirror area in space than its nearest relay competitor concept.

From an effectiveness standpoint, all of the laser concepts meet the minimum NMD requirements except for the ABL with Relay Mirrors architecture which can only kill 14 of the 20 ballistic missiles within the two minute timeline. This is probably not a serious detriment since the laser boost-phase defense is simply minimizing the targets for the rest of the NMD architecture. From a technological standpoint, the GBL with Relays architecture is the best because it has the required effectiveness with the best feasibility.

Operational Considerations

Operationally, the best laser NMD concept is ABL with Relay Mirrors. This architecture has the same reliability, accessibility, and flexibility benefits of the GBL architecture because both of their laser sources are available on the ground for operations, maintenance, and future upgrades. Additionally, while the ABL does not have the "deep magazine" of the GBL, it has the critical benefit of not having to worry about weather interfering with the supply of laser power. The SBL architectures all suffer because their component inaccessibility inhibits reliability and expandability options.

All of the laser architectures also possess capabilities to have operational benefits beyond NMD. This is one of the reasons that they were designed with lasers at 1.3 microns which has better atmospheric penetration. These systems not only have the ability to improve on the NMD requirements, but also to eventually expand into some adjunct mission areas outlined in Appendix C. Overall, ABL with Relay Mirrors wins the operational area despite not having the "deep magazine" of the GBL.

Fiscal Complexities

The ABL with Relay Mirrors architecture is at least as cheap as both the SBL or GBL with Relay Mirrors' concepts. This is because only a single laser source is required for this architecture and it is already under development. It is unclear if the eleven meter relay mirror size could drive the ABL with Relays costs above that of the SBL or GBL with Relay Mirrors' concepts. However, due to the high costs to fully develop and implement three ground or space based laser sources for those architectures, it is unlikely that the ABL relay mirrors could cost more. Thus while there is some ambiguity, the ABL with Relay Mirrors concept should be the least expensive of the architectures.

Political Ramifications

The bottom line is that the ABM Treaty will have to be changed no matter which NMD architecture is implemented and NMD must be implemented because it is now an issue of national survival. When the US could not defend itself against an USSR attack, the ABM treaty benefited the nation by supporting the National Security Strategy (Mutually Assured Destruction). Today the treaty only hurts the US against the WMD ballistic missile threats defined in our National Security Strategy. If this approach cannot be taken for political reasons, then the US should negotiate ABM Treaty changes based on the fact that none of the laser boost-phase architectures are applicable because they are "based on physical principles" not addressed in the treaty.

If the US decides not to take these approaches, then the ABL with Relay Mirrors concept is politically the best NMD architecture because the ABL is an already accepted Theater Missile Defense system as a part of the Helsinki Agreement. The GBL with Relays concept should also be more easily negotiable within the ABM Treaty, because it only increases the number of ABM sites from one to three. Finally, the SBL options would add a whole new class of space weapons to ABM Treaty negotiations which would be a political nightmare.

Flexible Relay Combination

One way to gain the best of all worlds is to synthesize the architectures to obtain their benefits without the risks. One option for accomplishing this is implementation of a flexible Relay Mirror architecture that could be fed by any of the laser sources. A possible design for this architecture, developed in Appendix H, has relay mirrors with a receive aperture of 6.5 meters that could accept a laser source from either the ABL, GBL, or an improved SBL. The relay transmit mirror is 6 meters in diameter and is much less risky technologically compared to the ABL Relay concept. This Relay design would allow the GBL or SBL sources to destroy 20 enemy ballistic missiles if those laser sources were implemented, while an ABL available for NMD operations could kill 5 missiles within the 2 minute requirement. This flexible relay mirror approach would have all the operational and political benefits of the Airborne Laser architecture while being technologically less risky and fiscally cheaper than the Airborne Laser with Relay Mirrors design discussed in Chapter 4.

An additional benefit of the flexible Relay option is that only those laser sources that are required need be implemented. Initially the ABL could provide a minimal boost-phase defense, while even a single GBL site would enable a 70% weather chance of being able to perform the full NMD boost-phase defense with GBL's "deep magazine." If future NMD or adjunct requirements dictated, the Relay Mirrors could also accept inputs from SBLs or additional GBLs to improve the available architectural firepower.

Notes

[1] Johnson, Alan, BG, USAF. *Progress to Deployment – The Users Perspective,* Quoting General Estes, USSPACECOM, Peterson AFB, CO.

Chapter 7

Conclusion

The most important national goal we can have is assured survival.

—President Ronald Reagan[1]

Today's US National Security Strategy recognizes the existence of threats with both the capability and will to use weapons of mass destruction launched by ballistic missiles. A National Missile Defense will soon be required to counter those threats. Laser weapons used in the boost-phase portion of a National Missile Defense architecture not only deter enemies, but can effectively destroy enemy ballistic missiles if required.

Four boost-phase laser architectures were evaluated against NMD technical, operational, fiscal and political criteria. The Space Based Laser (SBL), SBL with Relay Mirrors, Ground Based Laser with Relay Mirrors, and Airborne Laser with Relay Mirrors each meet NMD requirements with varying degrees of success. Overall, a flexible Relay Mirror architecture accepting multiple laser sources was found to produce the best NMD boost-phase defense while reducing potential technical, operational, and political issues.

This analysis shows that US Space Command should implement a Relay Mirror architecture able to accept multiple laser sources, such as the planned ABL or a future GBL. This enables a powerful boost-phase NMD capability with future expandability at minimal cost. Future improvements to this architecture could be implemented using SBL, GBL, or ABL sources as NMD or adjunct mission requirements increase.

Notes

[1] Office of Technical Assessment, *Ballistic Missile Defense Technologies*, (U.S. Government Printing Office, 1985), 31.

Appendix A

Typical Lasers for NMD

Table 1 identifies the laser types that are discussed in this paper. This is not an exclusive list of all the lasers that are being investigated by the military. In addition, all quoted power levels are speculations by the author based on the referenced literature.

Table 1. Possible Lasers for National Missile Defense

Laser Type	Wavelength	Current Power Levels	Atmospheric Transmission[1]
Chemical HF	2.7 – 2.9 microns	Alpha est. 2.2 MW[2 3]	0 – 10%
HF overtone	1.35 microns	65% HF Power[4]	95% +
DF	3.5 – 4.0 microns	MIRCL est. 2.2 MW[5]	≈ 100%
COIL	1.32 microns	ABL COIL est. 3 MW[6]	95% +

HF laser: "This chemical laser combines heated hydrogen (produced in a combustion chamber similar to the one in a rocket engine) with fluorine gas to produce excited hydrogen fluoride molecules. The laser that results radiates on multiple lines between 2.7 µm and 2.9 µm. These wavelengths transmit poorly through the atmosphere."[7]

HF overtone laser: Optical coatings on the HF laser can suppress the fundamental HF wavelengths and cause lasing at roughly 1.3 µm. This is in the experimental stage, however promising results with BMDO's Alpha laser show a 65% efficiency at low powers. This in effect is a system gain since the laser brightness is proportional to the square of the inverse of the laser frequency.[8]

DF laser: "The deuterium fluoride laser is chemically the same as the HF laser. However, the increased mass of heavy hydrogen, deuterium, shifts the laser wavelengths to between 3.5 μm and 4.0 μm. This range is superior to the HF range for transmission through the atmosphere."[9]

COIL laser: "In the chemical oxygen iodine laser (COIL) … excited atomic iodine is used as the lasing medium. The first step involves blowing chlorine gas past a basic hydrogen peroxide solution. Chlorine migrates into the liquid and reacts to produce excited oxygen molecules. Excited oxygen then escapes from the solution and is mixed downstream with molecular iodine. The iodine molecules are broken up and individual atoms are excited by a nearly resonant reaction with the oxygen in multiple reactions. This last transfer of energy leaves atomic iodine in an inverted population, and this takes place between the mirrors of the laser's resonator."[10] The COIL "radiates only in a single line at 1.315 μm" which has excellent atmospheric transmission.[11]

Notes

[1] Michael J. Muolo, *Space Handbook, An Analyst Guide*, (Air Command and Staff College AU-18, Maxwell AFB, AL, 1993), 247.

[2] Space and Missles Systems Center USAF, *Space Based Laser – Project Background*, http://www.afbmd.laafb.af.mil/ade/backgrnd.htm.

[3] Yang Peigen, "Progress in Chemical HF/DF Lasers", Jiguang Jishu: *Laser Technology*, (Vol 12, No. 3, Translated by Leo Kanner Associates for the National Air Intelligence Center, June 1988), 7.

[4] D. Wildt and S. Lissit, *Space-Based Chemical Lasers for Ballistic Missile Defense*, (AIAA 24th Plasmadynamics & Lasers Conference, Orlando FL, July 93), 6.

[5] Peigen, 7.

[6] Robert Braham, et al., "Ballistic Missile Defense: its back," *IEEE Spectrum*, (Sept 97), 43.

[7] Ibid., 42.

Notes

[8] Wildt, 6.
[9] Braham, 42.
[10] Ibid., 46.
[11] Ibid., 42.

Appendix B

Calculations of Critical NMD Requirements

Fluence levels required to kill North Korean Taepo Dong 2 missile

First, what does physics tells us? Using the Air University's Space Handbook calculations as an example, it is possible to calculate the laser fluence required for melting and then vaporizing a hole in skin of Taepo Dong 2 missile.[1]

Assuming that the Taepo Dong 2 has similar skin to that of its predecessor the NoDong, the calculations are done with a missile that has a steel skin with thickness of 3 millimeters.[2] Note that this is the thickest skin of any of the ballistic missiles on which detailed data could be found. It is 3 times the thickness of the Scud missile and 1.5 times the thickness of the SS-18 intercontinental ballistic missiles. This should make the calculations conservative.

First, the mass of steel to be destroyed in 1 square centimeter of the target missile must be calculated. This would imply that wherever the killing laser applies the required killing fluence (Joules per centimeter squared), the target's skin would be destroyed. Thus if the beam applies the fluence over a 1 meter diameter circle, that whole 1 meter circle of skin would be destroyed. This paper assumes that this amount of missile destruction would kill the missile.

Amount of steel in 1 cm^2 = volume of steel $\times$ density

= (1 cm^2 * .3 cm skin thickness) $\times$ 8.02g/ cm^3 = 2.41 grams

To calculate the energy required to heat 2.41 grams of steel to melting point of 1808 degrees Kelvin:

$= m \times c \times (Tm - To)$

= (2.41 grams) (4.6 $\times$ 10^6 erg/gmK)(1808K – 300K)

= 16.7 $\times$ 10^9 erg

Where the missile skin temperature is assumed to be at room temperature. This is conservative because the missiles skin temperature should be hotter due to air friction. Now that the steel is heated, to calculate the energy required to melt 2.41 grams of solid steel to liquid steel requires:

$= m \times Lm$

= (2.41 gram) (2.5 $\times$ 10^9 erg/gm)

= 6.0 $\times$ 10^9 erg

The sum of these two calculations gives the total energy required to melt the 2.41 grams of steel in every square centimeter of steel that the killing laser hits.

= 16.7$\times$10^9 erg + 6.0 $\times$10^9 erg = 22.7 $\times$10^9 erg = 2270 joules

To vaporize the skin of the missile requires raising the molten steel to its vaporization temperature of 3271 deg K.

$= m \times c \times (Tv - Tm)$

= (2.41 gm) (4.6 $\times$ 10^6 erg/gmK)(3271K – 1808K)

= 16.2 $\times$ 10^9 erg

Then to vaporize the missile’s skin requires:

$= m \times Lv$

$= (2.41 \text{ gram}) (6.2 \times 10^{10} \text{ erg/gm})$

$= 149 \times 10^9 \text{ erg}$

Therefore the total energy required to vaporize .3cm^3 of steel missile skin:

$= 22.7\times10^9 \text{ erg} + 16.2\times10^9 \text{ erg} + 149\times10^9 \text{ erg} = 188\times10^9 \text{ erg} = 19\text{Kj}$

This implies that if the skin of the NoDong booster absorbs 2.2 kJ/cm^2 of energy, the .3 cm thick skin would melt and if the skin absorbs 19 kJ/cm^2, the .3 cm skin thickness would be vaporized. This would vaporize a hole in the booster skin the size of the laser beam spot. The laser spot size of any of the examined options would be a minimum of 63 cm (or about 2 feet). Thus, if the NoDong booster absorbed 19 kJ/cm^2 energy from a directed laser, a 2 foot (minimum) hole would be vaporized in the booster skin. Obviously, vaporization kill mechanism sounds a little excessive (along with the required energy). However, there are several other considerations that must be taken into account before selecting the required laser killing energy. The first of these is the reflectivity of the booster skin material.

Before the laser energy can melt the skin, it must first be absorbed into the skin material and thus the reflectivity of the booster skin must be considered. Since all of the lasers under evaluation are in the infra-red region of the spectrum (λ = 1.3 microns for COIL and HF overtone), the reflectivity of the material is around 90% for steel[3]. This would seem to imply that the energy that really needs to be applied to the booster in the infra-red region of the spectrum is:

$S = S_{absorbed}/(1-R)$

$= S_{absorbed}/(1-.90)$

$= 10 \times$ Sabsorbed   i.e. That is 10 times the energy amounts that have been calculated above.

However, "since reflectivity may be much less in the molten state than in the solid state, the actual laser intensity necessary to reach Sv (energy for target vaporization) may not be much greater than the intensity necessary to reach Sm (energy for target melting)."[4] This implies that the energy required to vaporize the .3 cm of booster skin thickness is probably not much more than 10 * 2.2 kJ/cm², or around 22 kJ/cm².

However, is a two foot hole in the booster skin really required in order to kill it? Consider the stresses that are already in place on the booster in flight and the stresses that will be added by a laser attack. If the target surface absorbs the steel vaporization energy, "the reaction force from the evolving vapor might put a high pressure over the surface (where the laser is attacking) and contribute to such effects as buckling and spalling."[5] To get these effects, the laser would not have to apply the entire 22kJ/cm², that is to vaporize the entire .3 cm skin, it would only have to start vaporization of the steel on the booster surface. Thus the killing energy required to buckle the booster is much less than the calculated 22kJ/cm².

Another failure mode that has not been considered is just the metal weakening, without even melting or vaporization. If the steel of the NoDong missile skin was weakened by heating it above its characteristic failure point (733 degK for steel) the missile could fail by rupturing due to internal pressure or a heated arc along the missile could cause it to fail catastrophically.[6] The required energy to accomplish this would be:

$= m \times c \times (Tf - To)$

$= (2.41 \text{ grams}) (4.6 \times 10^6 \text{ erg/gmK})(733K – 300K)$

Accounting for reflectivity, this would be:

$$= 480 \text{ joules} \times 10 = 4.8\text{kJ}$$

Thus if 4.8 kJ/cm² were applied by a laser at the Taepo Dong's skin during the boost phase stresses, a structural failure would be induced.

A consideration that must be taken into account for any of these failure modes is that the missile will be in the boost phase when the laser attack takes place. Since most boosters are designed with material strengths less than twice the expected flight loads, any reduction of the skin strength below 50%, would cause the booster to fail. Thus, if only half the skin thickness is weakened, the wall strength will be equal to that of the flight loads and we can expect the booster to fail under maximum flight loads. This would imply that instead of the required 4.8 kJ/cm² of absorbed energy, only 2.4 kJ/cm² needs to be applied to weaken half the skin thickness. Recall that this has already been multiplied by a factor of 10 due to skin reflectivity, which is conservative.

From a calculation standpoint, we end up with a wide range of possible numbers for the energy required at the surface of the booster in order to kill it:

MINIMUM Fluence required: The minimum possible energy 2.4 kJ/cm². The failure mode would be an overstressing of the booster skin due to weakening one-half of the booster skin thickness. This is still conservative because the missile skin starts hotter than room temperature and the reflectivity quotient is less than the factor of 10 that is being used.

MAXIMUM) Fluence required: The maximum required energy is roughly 22 kJ/cm² which would allow the laser to vaporize a hole in the booster skin. This is also very conservative because even the start of vaporization at the booster skin surface applies enough energy to induce failure.

Without reviewing detailed test data from actual laser kills (which is classified), a reasonable assumption must be made. Since vaporization of a hole in the missile is not required to induce failure and since the 2.4 kJ/cm² is conservative, this booster hardness will be used in any following calculations to design the laser architectures. For a sanity check, popular media quotations were compared with this hardness value.

A minimum hardness value was given from a 1970's Army test against a Minuteman missile: "a late 1970's Army test showed 1,000 joules/cm² could destroy a Minuteman missile under boost conditions."[7] A more conservative answer of 10kJ/cm² was quoted by two sources. The American Physical Society assumes a "nominal booster hardness of 10kJ/cm²"[8] and the Air University Space Handbook says that "10 kilojoules properly applied will kill almost anything." This is based on two premises. "First, vaporizing 1 gram of almost anything requires almost 10 kilojoules; second, removal of 1 gram of material from some vital spot will destroy almost any target."[9] This range of values are consistent with the calculated booster hardness of 2.4 kJ/cm².

Time Available for NMD System to kill 1 Booster

In order to calculate the time available to kill a single booster, the first assumption that must be made is that only one satellite (either SBL or Relay) is available to kill the 20 Taepo Dong missiles. This assumption will minimize the number of satellites in the constellation. Thus the max range of the killing satellite (either SBL or Relay) is defined by its ability to kill 20 missiles, that is apply the 2.4 kJ/cm² to each of the missiles.

To calculate the time allowed for the laser to kill each target, the total time available to kill all the missiles must be known. The Office of Technical Assessment (OTA) states that “for current missiles, the boost phase lasts 3 to 5 minutes. However, not all this period is available for the defense to attack the boosters. The defensive system must first detect the launch, determine that there is actually an attack in progress, decide to engage the boosters, and allocate defensive weapon platforms to the boosters.”[10] However, the OTA also states that “with a 25 percent reduction in payload, a booster about the same size as MX could be built which would burn out in less than 1 minute at only 80 to 90 km.”[11] Therefore for a reasonable estimate of boost phase killing time is somewhere between 1 and 3 minutes. For the design of these laser architectures, 2 minutes will be used. Remember that this will define the maximum amount of time that any one satellite will have available to kill all 20 missiles. Since the missile engagements will not all take place at the maximum range of the laser weapons, the actual engagement time will be for any attack against ballistic missiles will be shorter.

The 120 seconds of vulnerable booster time has to be broken into 3 parts: acquisition, slew/settle, and firing times. The first part is the acquisition time that the single satellite will need to acquire and track the missile. Experiments conducted by the USAF Phillips Laboratory suggest that this locking and tracking stage could consume several seconds.[12] To be conservative, it will be assumed that 10 seconds are required for this stage. The second part of the laser attack time is for the slew and settle time of the (laser or relay) satellite as it moves its aiming point from one target to another. According to BMDO, one-half of a second is enough time to accomplish this maneuver if the targets are close enough together[13] (such as a multiple launch scenerio). To be conservative, 1.5 seconds for each target transition will be assumed. Using these two assumptions, the time left for a laser attack on each missile can be calculated by:

Time/missile = [Total Time – Acquisition Time – Slew/Settle Time]/20 missiles

= [120 secs – 10 secs acquisition - (1.5 secs slew $\times$ 20 missiles)]/20 missiles

= 4 seconds/missile

Thus 4 seconds is the maximum time that any NMD system will have available to kill a boosting missile. This will allow any laser NMD architecture to kill all 20 Taepo Dong 2 missiles in less than 2 minutes.

Power required at Missile Skin for Laser Kill

Since the required fluence to kill the Taepo Dong 2 missile has been calculated and only 4 seconds/missile has been allocated to kill the missile by the same laser satellite (either SBL or relay), it is now possible to calculate the power that must arrive at the missile skin in order to kill it.

P = Fluence/time

= 2400 joules/cm^2/4 seconds

= 600 Watts/cm^2

This means that any laser architecture will have to expose each of the 20 missile skins with at least 600 Watts/cm^2 for 4 seconds in order to achieve the 20 Taepo Dong kills.

Notes

[1] Michael J. Muolo, *Space Handbook, An Analyst Guide*, (Air Command and Staff College AU-18, Maxwell AFB, AL, 1993), 284.

[2] Robert Braham, et al., “Ballistic Missile Defense: its back,” *IEEE Spectrum*, (Sept 97), 47.

[3] Ibid., 48.

Notes

[4] Muolo, 296.

[5] Ibid., 297.

[6] Braham, 42.

[7] Michael A. Dornheim, “Alpha Chemical Laser Tests Affirm Design of Space-Based Weapon,” *Aviation Week and Space Technology*, (Jul 91), 26.

[8] American Physical Society. *Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons,* (New York, 1987), 55.

[9] Muolo, 286.

[10] Office of Technical Assessment. *Ballistic Missile Defense Technologies*, (U.S. Government Printing Office, 1985), 141-2.

[11] Office of Technical Assessment, *Directed Energy Missile Defense in Space–A Background Paper* , (U.S. Government Printing Office, April 1984), 8.

[12] Braham, 45.

[13]Space and Missles Systems Center USAF, *Space Space Based Laser – Project Background*, http://www.afbmd.laafb.af.mil/ade/backgrnd.htm.

Appendix C

Potential Adjunct Missions for Laser Architectures

Any laser system designed to kill ballistic missiles will have other capabilities that can be used by the military. A few of these potential missions are described below.

Offensive/Defensive Counter Air:. "To punch through the metal skin of an airplane requires about 700 joules per square centimeter."[1] The laser architectures developed in this paper could deliver this firepower in a little over a second to any spot on or over the earth. Enemy aircraft would be limited to flying through rain or clouds through which these lasers could not penetrate.

Offensive/Defensive Counter Space:. These laser architectures have the ability to perform Anti-Satellite missions. The target satellites could either be destroyed or their sensitive sensors damaged by the high energy lasers. Optical sensors in space (and on the ground) can be damaged with no more than 10 joules per square centimeter.[2]

Reconnaissance/Surveillance: The optics on the SBL or the Relay Mirrors have the capability to passively observe objects at high resolutions. Additionally the SBL could perform active imaging with a low power laser used as a target illumination source.[3] Either one of these sensing capabilities could be exploited as intelligence assets by tactical or strategic commanders.

Notes

[1] Major General Bengt Anderberg and Dr. Myron L. Wolbarsht, *Laser Weapons – The Dawn of a New Military Age,* (New York, 1992), 115.

[2] Ibid., 115.

[3] D. Wildt and S. Lissit, *Space-Based Chemical Lasers for Ballistic Missile Defense,* (AIAA 24th Plasmadynamics & Lasers Conference, Orlando FL, July 93), 4.

Appendix D

SBL Architecture Design

BMDO's brightness requirement for an operational SBL system is B=10^20 Watts/steradian.[1] Using the brightness formula: $B = P \times D^2/(1.2 \times \lambda^2)$, where B = system brightness, P = laser power, D = focussing mirror diameter, and λ = the laser wavelength, several options for the required laser power and mirror diameter can be calculated.

For a HF laser at 2.7 microns wavelength, this brightness could be produced with either an 8 meter mirror with 13.7 MW laser or 10 meter mirror with 8.7 MW laser. This agrees with an OTA assessment that says for an NMD system, a "reasonable HF laser brightness for a single large unit is 10MW and 10m mirror"[2] Another option is the HF overtone laser at 1.3 microns which is also being worked on by BMDO[3] this brightness could be produced by a 4 meter mirror with a 12.7 MW laser, a 5 meter mirror with 8.1 MW laser, or 6 meter mirror with 5.6 MW laser.

The best option for military use is the HF overtone laser, because this laser can penetrate the atmosphere and be used for force projection missions to the earth. In addition, since laser brightness is proportional to the square of the inverse of the wavelength, the same laser brightness can be obtained with a smaller mirror size. For the rest of the calculations, a 5.6 MW HF overtone laser with a 6 meter mirror will be used. Both of these are within BMDO's capabilities as discussed in Chapter 2 (SBL) of this paper. However, recognize that this is only one of several options that BMDO can use to get the same required laser brightness.

To calculate the details of the SBL constellation, the range at which the SBL will be effective must be calculated. Then this value can be used to produce an maximum altitude for the satellites. Using the booster hardness of 2.4 kJ/cm² and 4 seconds allocated to kill each missile (Appendix B), it is possible to calculate the maximum range that a SBL satellite can kill the ballistic missiles.

Max range = (tB/H)^.5,

where t is laser time on target, B is laser brightness, and H is the missile hardness.

Max range = [4 seconds × 10^20 Watts/steradian / 2.4 kJ/cm²]^.5

Max range = 4082 km

This means that at a range of 4082 kilometers, an SBL designed by BMDO can destroy a ballistic missile in 4 seconds or can destroy the entire 20 missiles in 120 seconds (see time calculations in Appendix B). To calculate the optimal altitude of the SBL satellites, the SBL will use this "killing range" of 4082 kilometers to cover the earth from horizon to horizon. To do this, the SBL must be placed at the proper altitude, so that the satellites horizon distance is 4082 km.

Figure 5 shows that $(r + h)^2 = r^2 + R^2$ where r is the radius of the earth (6378 km) and R is the maximum Range of the satellite (4082 km), and h is the correct altitude for the SBL satellite for horizon to horizon earth coverage. Therefore $h^2 + 2rh - R^2 = 0$ and applying the quadratic formula, we get:

$$h = \{-2r +/- \sqrt{[(2r)^2 + (4 \times R^2)]}\}/2$$

$$= \{-12756 +/- \sqrt{[(12756)^2 + (4 \times (4082)^2)]}\}/2$$

= 1194 or roughly 1200 km

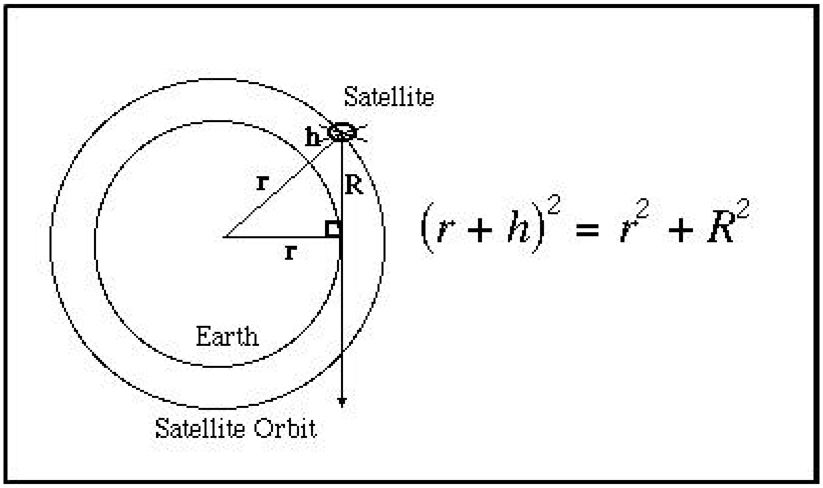

Figure 5. Calculation of Optimal SBL Altitude

Also using the diagram, we can calculate the field of view (FOV) of the satellite. The FOV is the half-angle that the satellite is responsible for covering as it is looking towards the earth. In this case, the FOV is from horizon to horizon for the satellite. Looking at the diagram, we can see that:

FOV = invtan (r/R)

= invtan(6378/4082)

= 57.4 degrees

Using the SBL satellite's optimum altitude (that minimizes constellation size) and its FOV, it is possible to build an SBL architecture using on orbital simulation tool such as the Satellite Orbit Analysis Program (SOAP) written by the Aerospace Corporation. Figure 6 shows the results of SOAP simulations which used 24 SBL satellites at an altitude of 1200 kilometers. This number of satellites allowed it to constantly cover the earth and thus enable the satellite constellation to fire on boost phase ballistic missiles, no matter where they are launched.

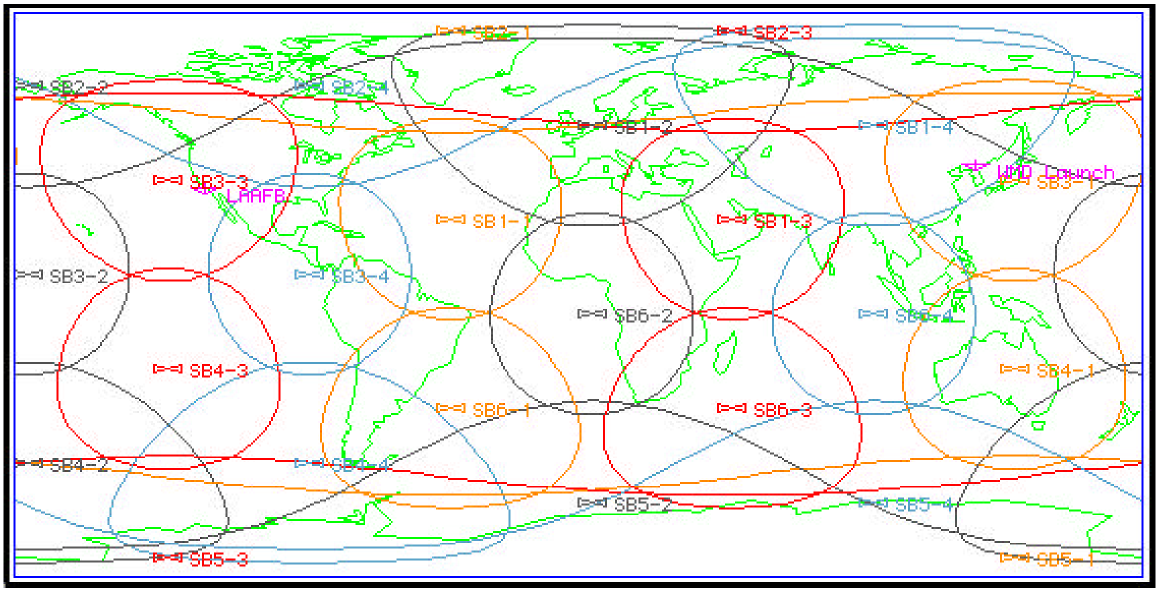

Figure 6. SBL Constellation showing Satellite Views

Figure 6 shows each of the SBL satellites area of view as a colored circle/oval. The satellites are positioned so that there are 4 orbital planes (separated by 45 degrees in right ascension) with 6 satellites in each. All of the SBL orbital planes are in polar (inclination = 90 degrees) orbits so that they could have full earth coverage and still be in an inclination that could be launched from a major US launch site. In this case, the SBL launches could all occur from Vandenberg AFB, which has direct access to polar orbits.

Lower orbital inclinations were evaluated down to 70 degrees, which would allow the satellites to have more coverage at lower earth latitudes, however these lower inclination orbits were not considered to be more optimal for 2 reasons. Launching from Vandenberg AFB into lower inclinations would require launching into a retrograde orbit which reduces the liftable payload weight, a premium in the SBL design. In addition, placing the satellites into lower inclinations in these simulations did not reduce the 24 total SBL satellites required for full earth coverage. Other variations of orbital constellations were also simulated, with 24 satellites being the lowest number that could provide this full earth coverage.

In the final design, the orbital inclination, payload weight, and earth coverage will all have to be optimized. For purposes of evaluating the SBL design, polar orbits will be used because all inclinations from 70 to 90 degrees provide full coverage with 24 satellites and 90 degrees inclination maximized launch weight. The final configuration of 24 satellites in 4 polar orbits, identified by the dash numbers on the satellites, can be seen better from the North Pole view in Figure 7.

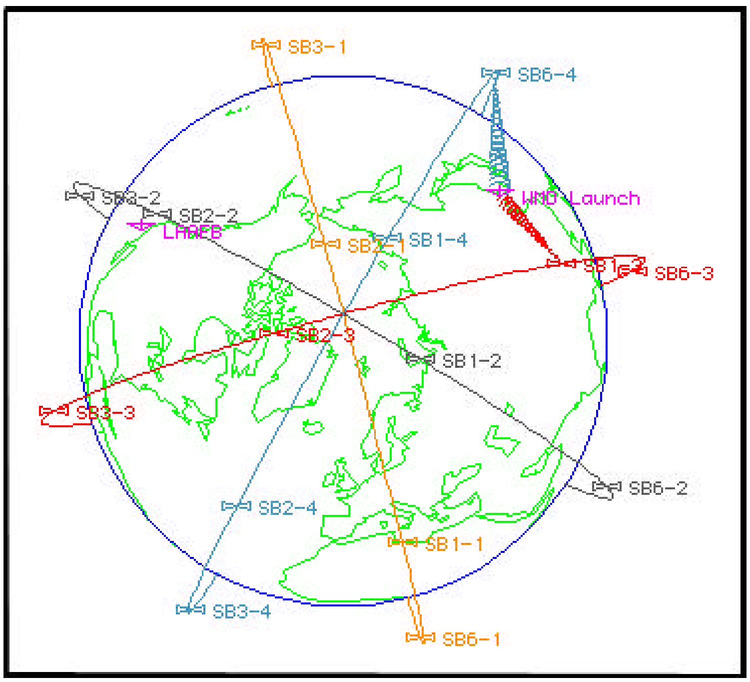

Figure 7. SBL Constellation Orbital Planes

Figure 7 also shows two satellites having a simultaneous view of a ballistic WMD launch. While these 2 satellites provide redundant coverage in this situation, small gaps do occur in the constellation as the satellites orbit the earth. In order to understand if these gaps were significant, this SBL architecture was simulated against a WMD launch from North Korea. The results are shown in Figure 8.

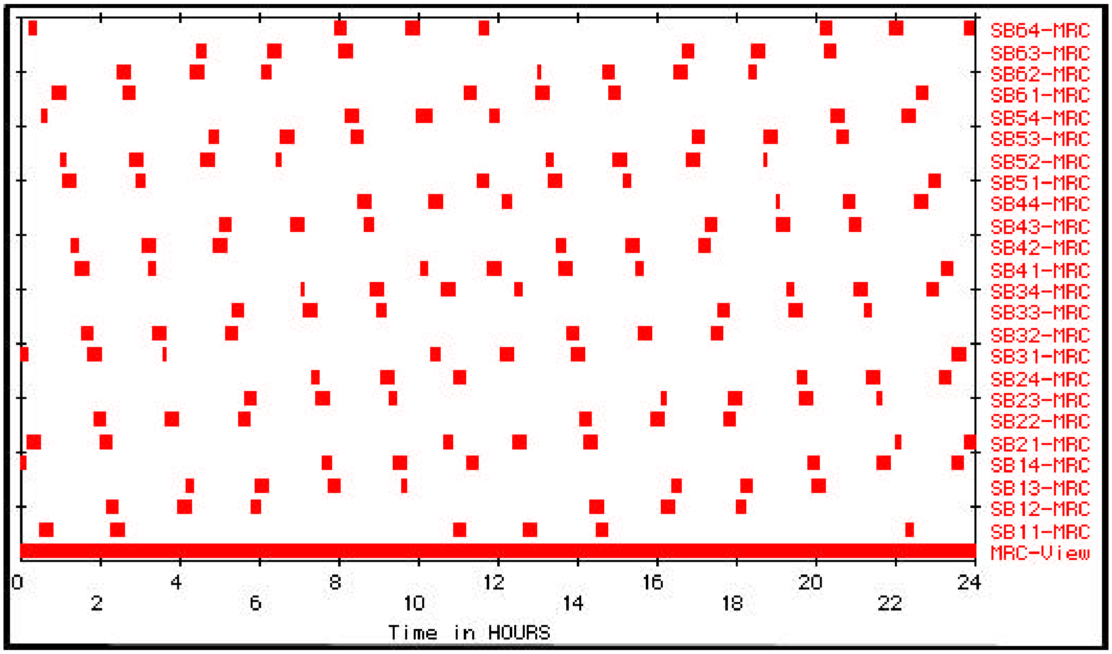

Figure 8. SBL Constellation View of Missile Launch

This SOAP simulation was run so that any gap of more than 1 minute in the coverage of the WMD launch from the Korean MRC would be shown. Each of the satellite labels (SBxx) shows when they are viewing the MRC area that has the ballistic missile launch. The bottom label (MRC-View) is the summation of all the SBL views over a 24 hour period. It shows that there are no gaps in the SBL coverage of more than 1 minute. These small gaps in the constellation are significant, because even if a ballistic missile launch is planned into a satellite gap, the gap is closed within 1 minute. Additionally, when the constellation exposes a gap in its coverage, the gap is closed by 2 satellites having overlapping coverage of the same area. This is important because each satellite can destroy 20 missiles at its maximum range (4082 km) and thus a missile barrage launched into a gap is soon covered by 2 satellites with a potential to kill more than 40 missiles.

Figure 9 shows 2 SBLs of the 24 total satellites attacking the ballistic missile launch with all of the available satellites views. These SBLs are built with 5.6MW lasers and 6 meter primary mirrors which produce BMDO's required brightness of 10^20 MW/steradian. As discussed, this arrangement of 4 orbits of 24 SBLs allow this architecture to satisfy all of the NMD requirements.

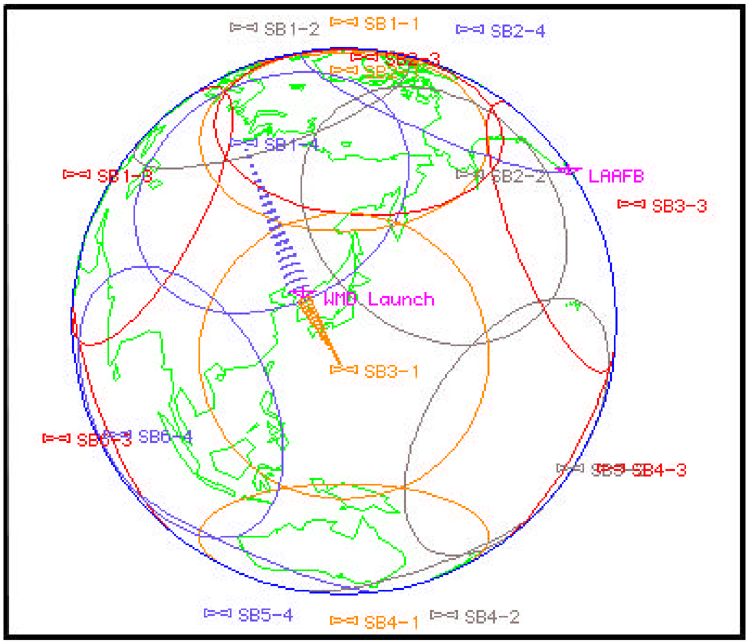

Figure 9. SBL Constellation Attack on WMD Ballistic Missile

Notes

[1] Colonel Loverro, *Space Based Laser The Path Ahead,* Briefing for USAF SMC/AD, (17 Dec 97), 5.

[2] Office of Technical Assessment. *SDI Technology, Survivability, and Software,* (First Princeton University Press, 1988), 138.

[3] Clifford H. Mueller, *Department of Defense High Power Laser Program Guidance,* Phillips Laboratory, Kirtland AFB, NM, (6 June 94), ii.

Appendix E

SBL with Relays Architecture Design

To start the planning for a SBL with Relay Mirror Architecture, two major types of relay mirrors need to be considered. The Monocle is a single mirror relay design and the Bifocal is a two mirror relay design. Figure 10 shows rough concepts of these two design options.

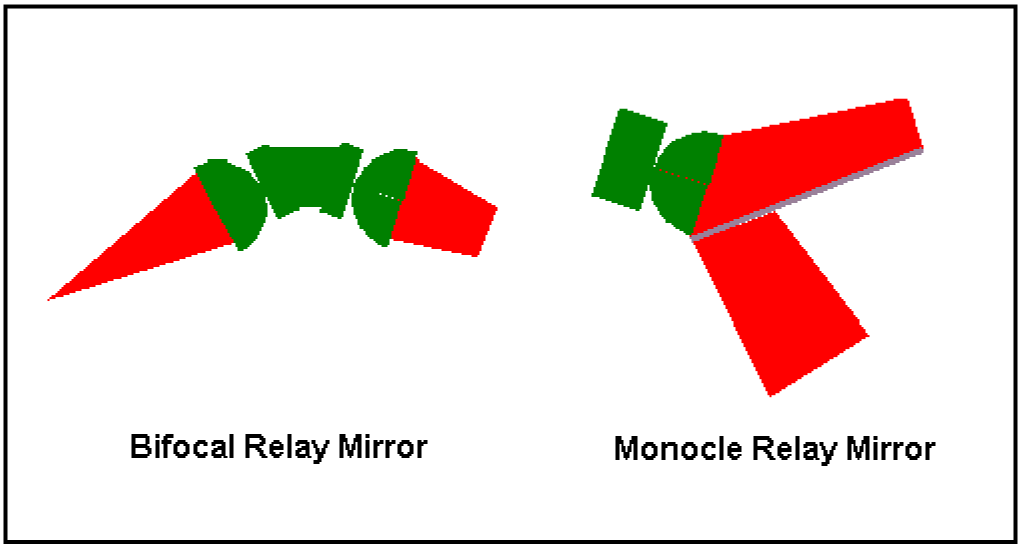

Figure 10. Bifocal Vs. Monocle Relay Mirror

Each of the relay designs have pros and cons, but the critical factor is that while the monocle design is easier to manufacture and the bifocal design has the technical concern of requiring small high power mirrors, the bifocal refocuses of the laser on the target while the monocle allows the beam to continue its divergence.[1] [2] This is important because by using a series of smaller mirrors (SBL primary to Relay receive aperture to

Relay transmit aperture), the same killing power can be placed on the target without significantly increasing the SBLs brightness. This will be demonstrated later in the calculations.

In order to build the SBL with Relay Mirror Architecture, altitudes need to be calculated for both the SBLs and the Relay Mirrors. For ease of calculations, the relay mirrors can take up the orbital parameters of the SBL constellation generated in Appendix D. This means that the Relay constellation is 24 bifocal relay satellites in 4 polar orbits at an orbital altitude of 1200 kilometers with each relay being able to transmit killing power to the maximum range of 4082 kilometers. This constellation has already been proven in Appendix D to provide full earth coverage.

It is not really necessary to calculate an altitude for the SBL satellite that will feed this architecture. Technically, the SBL can fire at any relay satellite which can then pass the laser from relay to relay until it gets to the ballistic missiles. However, each transition to and through a relay satellite has system loses estimated at 20%[3], therefor an SBL orbit should be used that minimizes these losses. In order to do this, the SBL satellites were placed in a equatorial orbit at an altitude that would allow them to see all the satellites on their half of the globe. In this configuration, while 2 SBL satellites could feed the entire Relay Mirror constellation, 3 were used to provide overlap in coverage. Figure 11 shows the diagram which allowed the calculation of the correct SBL altitude.

The major constraints in this calculation arse that the relay mirrors directly over the poles must be visible without the transiting laser beam passing the atmosphere (100km altitude).

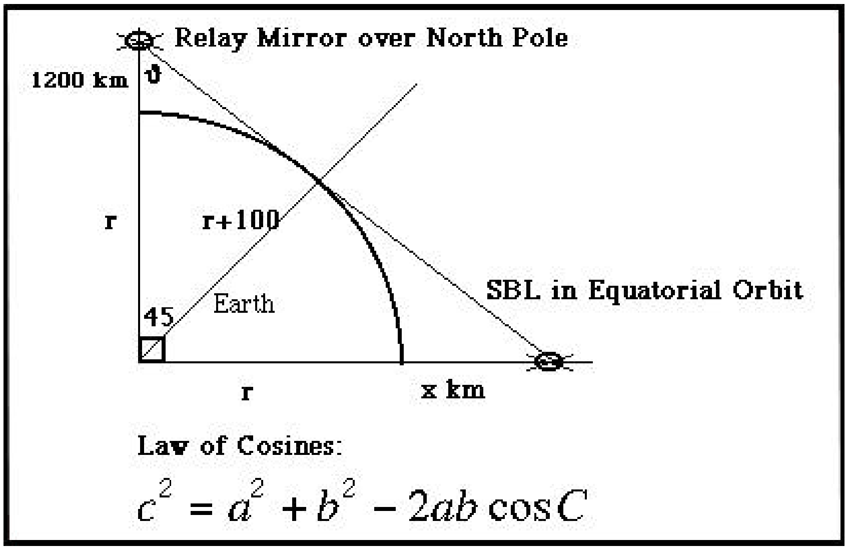

Figure 11. Calculation of SBL Orbital Altitude

Figure 11 shows that the law of cosines can be used to calculate the SBL altitude:

$c^2 = a^2 + b^2 - (2 \times a \times b \times \cos C)$

$c^2 = (r+1200)^2 + (r+100)^2 - [2 \times (r+1200) \times (r+100) \times \cos 45]$ where $r = 6378$ km

$c = 5474$ km

And again using the law of cosines to find θ:

$c^2 = a^2 + b^2 - (2 \times a \times b \times \cos C)$

$\cos C = (a^2 + b^2 - c^2)/(2 \times a \times b)$

$\cos\theta = [(r+1200)^2 + (5474)^2 - (r+100)^2]/[2 \times (r+1200) \times (5474)]$

$\theta \geq \text{invcos}\ (.5475)$

$\theta \geq 56.8$ degrees

The minimum SBL altitude (h) can be calculated by:

$\tan(\theta) = [(r + \text{SBL altitude})/(r + \text{Relay altitude})]$

$\tan(56.8) = [(6378 + x)/(6378 + 1200)]$

$h = 5200$ kilometers

Using 5200 kilometers for the SBL satellite altitude, the maximum SBL firing range can be determined. This will determine the receive aperture of the Relay satellite.

$$Rmax^2 = [(\text{Relay altitude})^2 + (\text{SBL altitude})^2]$$

$$Rmax = [(6378 + 1200)^2 + (6378 + 5200)^2]^{.5}$$

$$Rmax = 13{,}837 \text{ kilometers}$$

If we use the same SBL primary mirror design as in Appendix C with a 6 meter aperture, then we can determine the receive aperture required on the Relay Mirrors by determining the spot size of the laser as it arrives at its max range.

$$Dspot = 2.44 \times Rmax \times \lambda \text{ laser} / Dtransmit$$

$$Dspot = 2.44 \times 13{,}837{,}000 \text{ meters} \times (1.3 \times 10^{-6} \text{ meters}) / 6 \text{ meters}$$

$$Dspot = 7.3 \text{ meters}$$

Thus for this design the receive aperture of the Relay satellites is 7.3 meters. This is a tradable size based on the SBL primary aperture size. If it was optimal (due to manufacturing cost, launch vehicle constraints, etc…) to have the Relay's receive aperture the same size (or smaller) than the Relay satellite's transmit aperture, then this could be adjusted based on the SBL's transmit aperture or the SBL orbit. As an example, if the receive aperture had to be 6 meters in diameter, then the SBLs transmit aperture could be increased to 7.3 meters. This would have to be optimized during system design. For ease of comparison with the other laser architectures, a SBL transmit aperture of 6 meters and a Relay receive aperture of 7.3 meters are used.

If the monocle mirror design had been used the SBL transmit aperture would have been a bigger problem. The maximum range that the SBL would have to focus a killing power would have been 13,837 kilometers from the SBL to the Relay and an additional

4082 kilometers to the maximum target. In order to focus the killing power of 600 Watts/cm² on the target, this would have required the SBL to have a primary mirror sized to:

$$D = [(1.2 \times Rmax^2 \times \text{missile hardness} \times \lambda^2)/(\text{laser power} \times \text{time to kill})]^{.5}$$

$$= [(1.2 \times (13{,}837{,}000+4{,}082{,}000\ m)^2 \times (2.4\times10^{7}\ J/m^2) \times (1.3\times10^{-6} m)^2) /((5.6\times10^{6}\ \text{Watts}) \times (4\ \text{second}))]^{.5}$$

$$= 28 \text{ meters}$$

This is a practical demonstration of the benefit of bifocal relay mirrors. By using the bifocal mirror and allowing it to refocus the laser energy on target, all of the primary optics can stay below 7.3 meters. If a monocle relay mirror design had been used, the SBL laser brightness would have had to be increased by using a SBL primary mirror of 28 meters. This is much larger than current capabilities.

The last parameter that needs to be calculated is a revised laser power for the SBL. Since the architecture has been designed so that the laser firing only passes through one relay, losses for only a single 20% loss factor[4] needs to be used. These losses consist of losses in the transmission from the SBL to the Relay and internal Relay losses. The SBL laser brightness must increase by 20% to make up for these losses and give the Relay Mirrors the same killing range of 4082 km. This means that the laser power can be increased by 20% to 6.7 MW or the primary mirror diameter can be increased by the square root of 20% (9%) to 6.6 meters. Either is achievable given the capabilities that BMDO has shown to date (see Chapter 2), however increasing the laser power will allow the SBL primary mirror to stay at 6 meters and thus be the same size as the Relay transmit mirror. As was stated earlier, this architecture could also operate with only 1

SBL satellite, however transmission losses would have to be increased to account for the SBL laser passing through multiple relay satellites to kill the ballistic missiles.

These calculations produce a robust SBL with Relay Mirror architecture. It consist of 24 Relay Mirrors in 4 polar orbits with 6 satellites each. They have a 7.3 meter receive aperture and a 6 meter transmit aperture. It was shown in Appendix D and also in Figure 12 that this relay configuration will provide full earth coverage for ballistic missile launches.

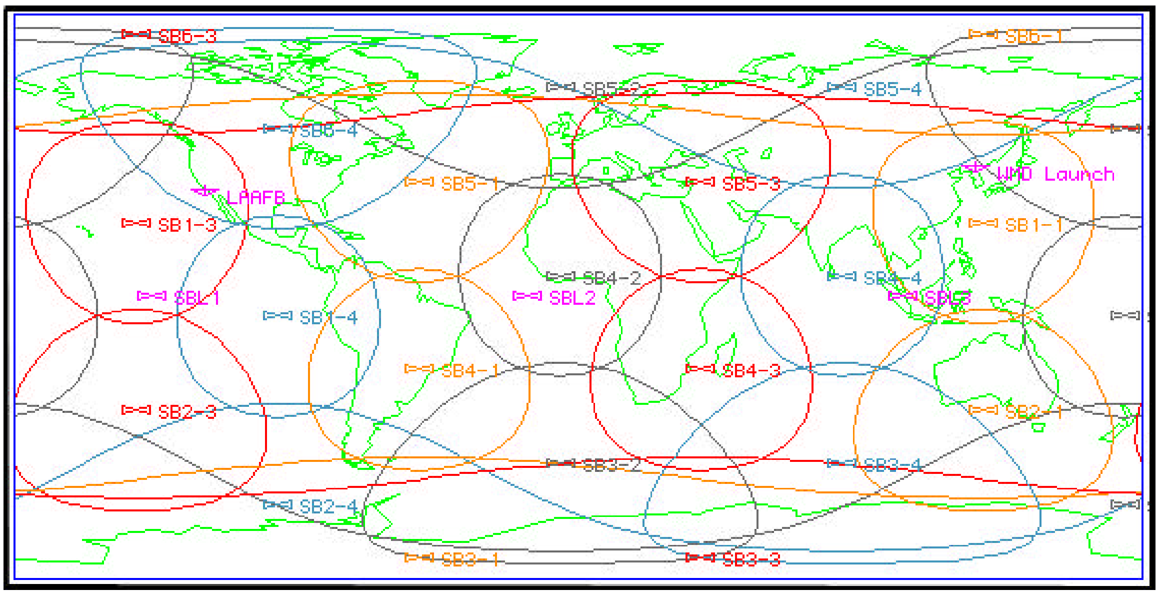

Figure 12. Full Earth Coverage of Relay Satellites

This relay satellite constellation is fed laser power by 3 SBL satellites in a equatorial orbit at 5200 kilometers altitude. The SBLs use 6 meter primary mirrors to transmit a 6.7 MW HF overtone laser. Figure 13 shows the final orbits of all satellites in this constellation.

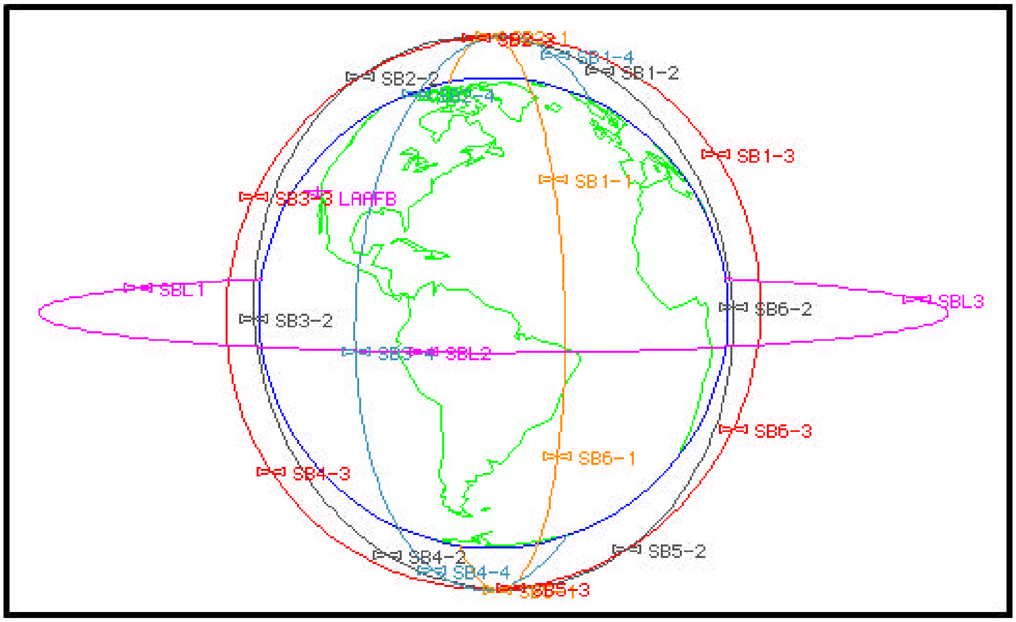

Figure 13. Orbits of SBL with Relay Mirror Architecture

In order to insure that every Relay satellite was continually in view of a SBL satellite, a linkage analysis was run as a part of the architecture simulation. Each of the 24 Relay Mirrors was examined over a 24 hour period to ensure that an SBL was always in view. Figure 14 shows a 6 satellite portion of this analysis. The line labeled, SB##View shows the total coverage of that particular relay satellite, while each of the 3 dash numbers (-1, -2, -3) shows which SBL has the relay satellite in view during the 24 hours. These results shown in Figure 14 demonstrate that all of the relay satellites could be provided laser power by the SBL satellites when required.

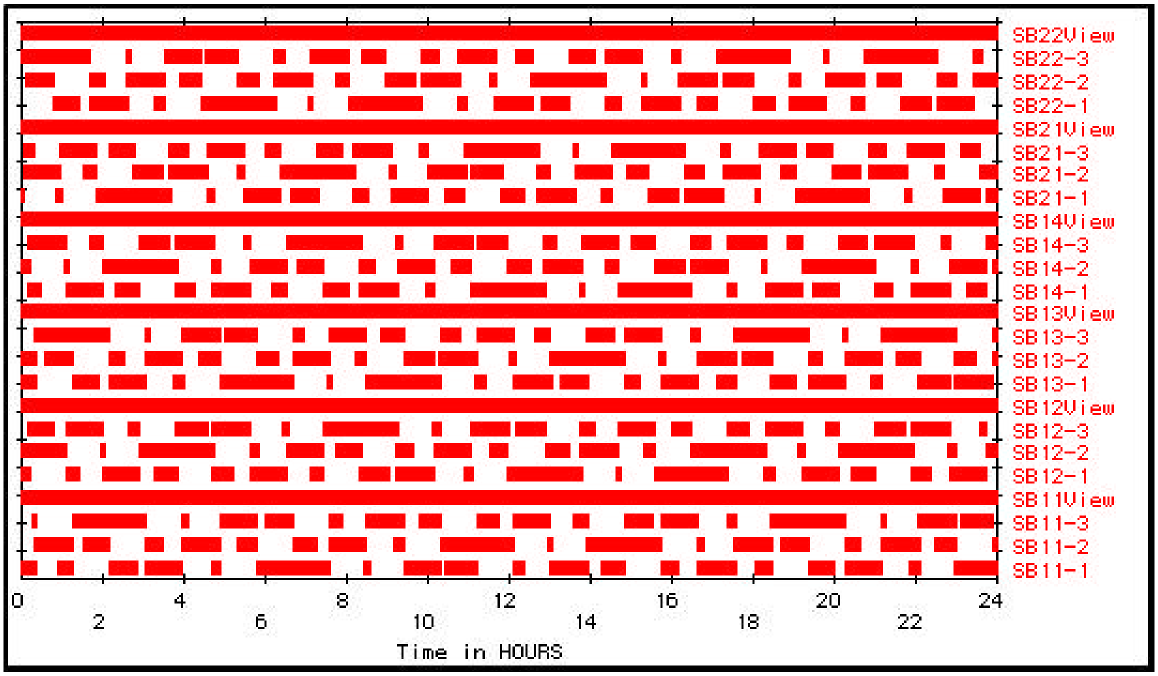

Figure 14. Relay Satellite Coverage by SBLs

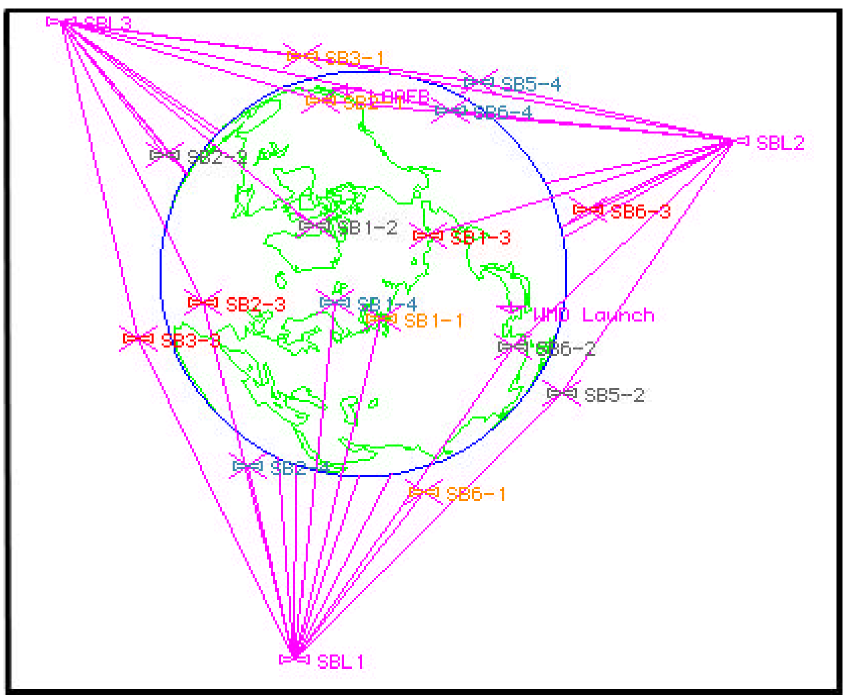

Figure 15. Links from SBLs to all possible Relay Mirrors

Figure 15 shows all of the possible linkages from 3 SBL satellites to the lower orbit Relay Mirrors. As you can see, because of using 3 SBL satellites, many of the Relays are visible to more than one SBL. This provides added robustness to the constellation.

Figure 16 shows a simulated ballistic missile launch from the Korean Peninsula. In this particular scenario, two Relay Mirrors (SB1-3 and SB6-2) have views of the missile launch and individually have the capabilities to kill a minimum of 20 ballistic missiles. Relay Mirror SB6-2 can be fed laser energy by SBL1 while SBL2 can feed either Relay Mirror SB6-2 or SB1-3. Another successful kill, another successful laser NMD architecture.

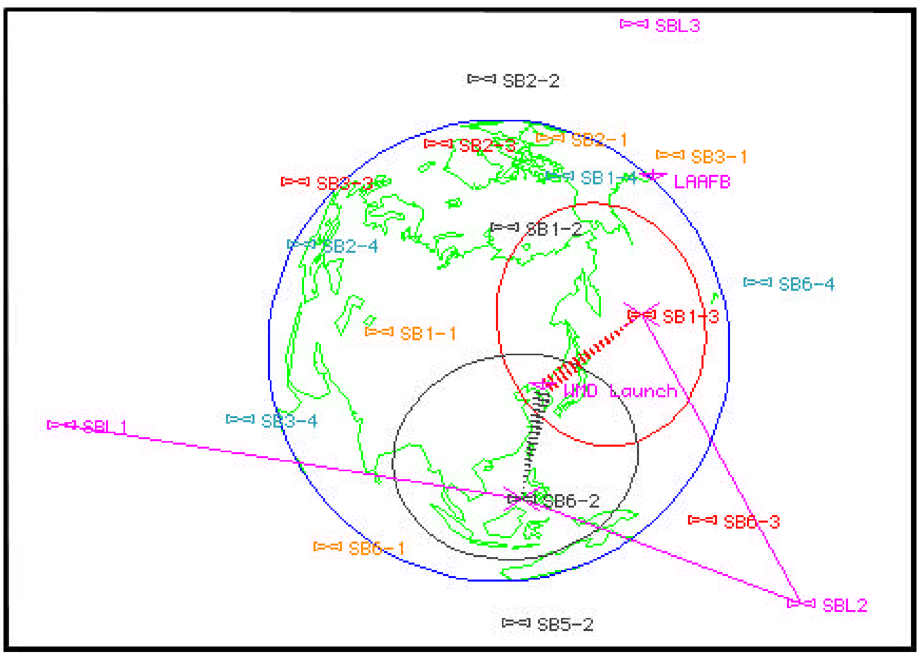

Figure 16. SBL with Relay Mirrors Against a Ballistic Missile Launch

Notes

[1] Lawrence Sher, *Optical Concepts for Space Relay Mirrors.* Phillips Laboratory, NM.

[2] Lawrence Sher and USAF Capt. Stephen Mcnamara. "Relay Mirrors for Space Based Lasers," *Laser Digest*, Air Force Weapons Laboratory, to be published.

[3] Sher, *Optical Concepts for Space Relay Mirrors*.

Notes

[4] Ibid.

Appendix F

GBL w/Relays Architecture Design

To build the GBL with Relays architecture, the laser source must first be considered. Specifically, will the GBL site be cloudless at the time that the laser needs to be fired? According to the American Physical Society, at least five geographically separated GBL sites must be provided in order to have a 99.7% chance that at least one site will be free from adverse weather during a ballistic missile attack,. These sites must be separated by at least 1000 kilometers, which is the coherence distance for weather patterns.[1] If the GBL sites have independent weather (separated by coherence distance), then the weather probability curve looks like:

1 GBL site: 70%

2 GBL sites: 91%

3 GBL sites: 97.3%

4 GBL sites: 99.2%

5 GBL sites: 99.7%

Thus using only 3 sites would provide a 97.3% chance that the GBL based architecture would be operational. This would obviously be a trade decision during implementation, but for a boost phase system this not only seems reasonable, it is comparable to normal satellite availability requirements. Therefore, 3 GBL sites were placed throughout the US to provide the laser source for this architecture.

The Relay Mirror satellites for this GBL architecture are in the same configuration as used in the SBL with Relay Mirrors architecture. This 24 satellite constellation was proven to provide full earth coverage in Appendix D. By placing the receiving relay mirrors in low earth orbits, the GBL sources must be able to track a moving relay mirror, but it also minimizes impacts due to thermal blooming. This will be discussed later in this Appendix. Figure 17 shows the visibility of the GBL sources to the receiving relay mirrors.

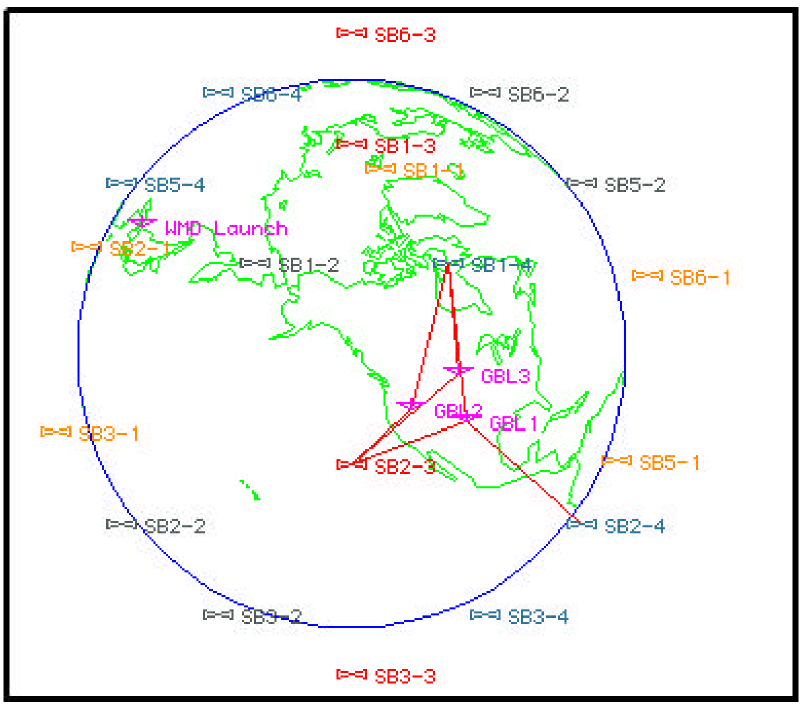

Figure 17. GBL to Relay Mirror Links

As was shown in Appendix D, these 24 relay mirrors will have a 6 meter transmit aperture that allows them to provide world wide coverage of any enemy ballistic missile launch. The relay mirror receive aperture has to be recalculated because the laser source is now provided by the GBL. The driving consideration for this aperture size is the passing of the laser from one relay to another relay as the beam gets passed to the missile target. Since the Relays are separated by 60 degrees in mean anomaly, this maximum relay transmit range will be the same as their height (creates an equilateral triangle) or 6378 km + 1200 km = 7578 km. Thus the relay receive aperture is calculated by:

$$\text{Dreceive} = 2.44 \times \text{Range} \times \lambda(\text{laser wavelength})/\text{Dtransmit}$$

$$= 2.44 \times 7{,}578{,}000 \text{ meters} \times 1.3\times 10\text{\^{}-6 meters/6 meters}$$

$$= 4.0 \text{ meters}$$

Recall that the SBL with Relay Mirror architecture (Appendix D) had relay mirrors with a 7.3 meter receive aperture. This 4.0 meter receive aperture would weigh less and reduce the cost to the design and build of the Relay Mirror satellites.

The only other parameter that needs to be determined is the power required to be transmitted by the GBL to meet the NMD required kills. Recall from Appendix B, that the attacking mirror needs to deliver 600 Watts/cm² to the ballistic missile surface for 4 seconds in order to meet the required killing fluence at the missile.

There are 2 features that try to prevent the GBL from delivering that required laser energy: architecture losses and atmosphere losses. Additionally, atmospheric losses break down into transmission, turbulence and blooming losses. Each of these will be examined to see how they affect the GBL system architecture.

The architecture losses are those losses that occur as the laser energy is transmitted from one relay mirror to another. Since the relay receive mirrors only large enough to capture the laser's Airy disk, the best transfer efficiency that can be expected is 84%. If we include other system inefficiencies inherent like beam jitter and mirror losses, this is probably closer to 80% for each laser energy transfer.[2] Therefore, in the GBL constellation, the architecture losses would be 80% for each of the Relay mirrors that the laser beam has to pass through to get to the target. This is the same factor that has been used in each of the other relay satellite architectures.

With 6 satellites in each orbital plane, the largest number of relays that the laser could have to pass through is 4. This is demonstrated in Figure 18 which passes the laser to the opposite side of the Earth in 4 transitions. Notice that any of the GBL sites could hit Relay SB2-4. This relay would then pass the laser to Relay SB1-4 almost over the North Pole. The last two transfers through Relays SB6-4 and SB5-4 complete the movement to the opposite side of the earth. Figure 18 demonstrates that there is not any spot on earth more than 4 relay passes away from the GBL sites in the United States and Figure 19 shows all of the relay possible linkages.

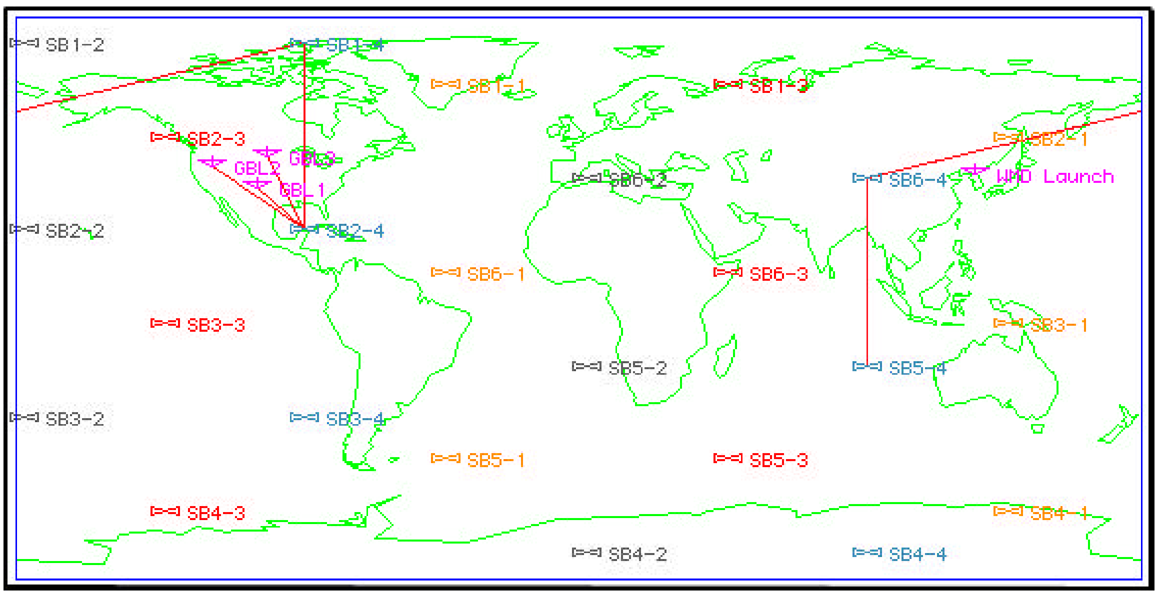

Figure 18. GBL Laser Relay to Opposite Side of Earth

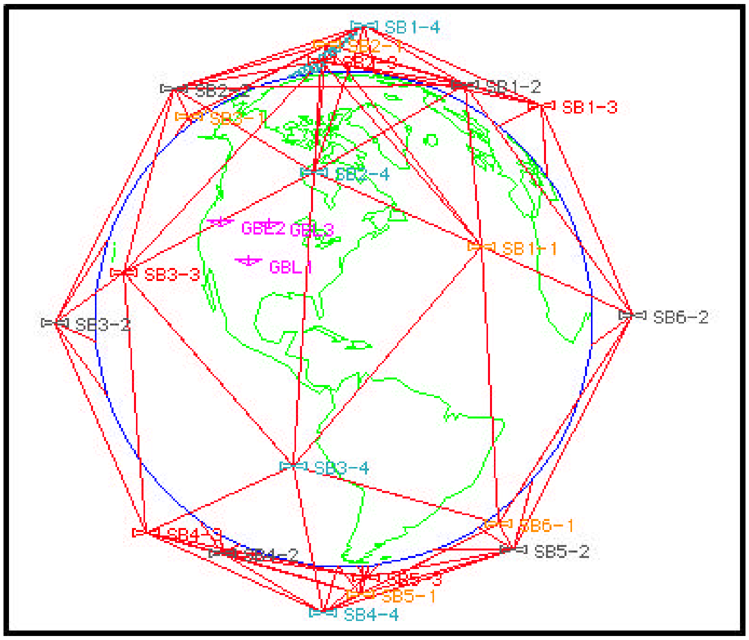

Figure 19. All Possible Relay Linkages

Using 4 relay satellites has a architecture loss penalty of 80% × 80% × 80% × 80% = 41%. Knowing the architecture efficiency is 41%, the laser power that needs to survive the trip through the atmosphere can be calculated. This would be 5.6 MW/.41 or 13.7 MW. Thus 13.7 MW has to get above the atmosphere for the GBL architecture as designed to work. So the next question is: what laser power needs to be fired from the GBL site in order to get this 13.7 MW above the atmosphere?

In order to answer this question, atmospheric losses need to be addressed. These losses occur because the laser must pass through the atmosphere during the GBL to relay mirror laser path. The transmission, turbulence and blooming parts of the atmospheric losses will each be addressed in turn.

Transmission losses are those that the laser loses due to absorption and scattering as the laser wavelength passes through the atmosphere. At the HF overtone wavelength of 1.3 microns that is being used, the transmission is nearly perfect or 100%.[3] Thus this part of the atmospheric losses is not a serious concern. Turbulence losses on the other hand, can be an issue if not handled correctly.

Turbulence occurs because the atmosphere is not a homogeneous medium. Variations in temperature, pressure, and humidity lead to random variations in the atmosphere's index of refraction as seen by the propagating laser beam. Turbulence can "change the amplitude of the beam as well as cause beam wander and beam breakup. If the beam is from a HEL [High Energy Laser] used as a weapon, turbulence can severely reduce the average intensity of the beam at the target aimpoint and vitiate the weapon's effectiveness."[4] Left uncorrected, the laser beam would diverge two or three orders of magnitude beyond its diffraction limit.[5]

"To counteract these atmospheric distortions, information from an additional 'beacon' laser beam is used to preshape a deformable mirror that correctly adjusts the killing beam" using adaptive optics.[6] Adaptive optics take the phase information from the beacon laser to preshape the deformable mirror so that it can correct the High Energy Laser's phase before it is even transmitted. This can be accomplished because atmospheric turbulence only affects the laser's phase (and not magnitude) in most GBL systems.[7] This is because most of the atmosphere is located within a few kilometers of the earth's surface and for most ground-based infrared systems with telescopes in the meter class, virtually the entire atmosphere lies within the near field of the system. "Thus if the adaptive optics system does a good job of correcting the phase, the resulting performance will be near the diffraction limit of the system."[8] Thus, a good assumption for turbulence losses with the appropriate adaptive optics system is probably around 95%.

The last atmospheric loss that needs to be considered is that of laser beam blooming. It was stated earlier that the transmission of the 1.3 micron laser in the atmosphere was nearly perfect, however the “nearly” part of the statement is what drives the nonlinear effect of blooming. Blooming occurs when the 1.3 micron laser energy is absorbed by aerosols (water droplets). As the laser energy is absorbed by the aerosols, the column of air that the laser is passing through is being heated nearly uniformly along its length. Thus in order to expand, the air must expand radially outward. This radial movement of molecules along the laser beam produces a drop in the density of the air along the central axis of beam.[9] This causes the air index of diffraction to change continually along the beam radius and thus creates a lensing effect, spreading the laser beam much more than what is predicted by diffraction optics.

The thermal distortion coefficient characterizes this heating of air in the beam path of a high energy laser and subsequent beam distortion. Calculation of the thermal coefficient for any given high energy laser system involves integration along the beam path of the absorption profile, air temperature, and crosswind velocity (both slewing and natural wind).[10] Without going into the depths of this calculation, two points can be made:

1) Keeping the thermal distortion coefficient below certain criteria allows the correction of the laser defocus by use of the adaptive optics techniques discussed above. For example, if the coefficient is kept below 100, then the Strehl ratio (which defines the percentage of the main lobe of the laser that arrives on target) can be corrected to roughly 95%.[11]

2) The calculation for the thermal distortion coefficient has the cross-wind velocity (including slewing) in the denominator of the equation.[12] Thus keeping the relay satellites in low earth orbit helps to mitigate the laser distortion due to thermal blooming. For the types low earth relay constellations under examination here, the thermal distortion coefficient can be reduced as much as a factor of 10 over the similar calculations for relays in a geosynchronous orbit.

Thus by using low earth orbit relays and keeping the thermal distortion coefficient to reasonable values, it is possible to reduce the impacts due to blooming. For purposes of these GBL calculations, simulations of beam control software used to correct for the blooming show that the laser focus (Strehl) can be recovered to 92%.[13] This is also consistent with experiments that have shown achievable Strehl ratios to be around 90% when correcting for both turbulence and blooming.[14] With this, the final GBL transmit power can be calculated. Since 13.7 MW need to arrive at the relay satellites, the GBL site needs to transmit 13.7 MW/(95% $\times$ 92%) = 15.7 MW.

If the GBL transmits the 15.7MW with a 4 meter primary mirror then the maximum range to the relay mirror is 4,082 km and the relay receive aperture has to be:

Dreceive = 2.44 $\times$ Range $\times$ λ(laser wavelength)/Dtransmit

= 2.44 $\times$ 4,082,000 meters $\times$ 1.3$\times$ 10^-6 meters/4 meters

= 3.2 meters

Since the relay receive apertures are already 4.0 meters which is driven by the relay to relay transfer, this is not an issue.

Therefor, the final GBL architecture looks like:

1) 3 GBL ground sites separated by 1000km which give a 97.3% chance that one site will be weather free for transmission. These GBLs are able to track the low earth orbit relays. Their transmit mirrors are greater than 4 meters in diameter and fire a minimum of 15.7 MW 1.3 micron lasers which have been corrected for transmission by a adaptive optics system.

2) 24 fighting relay mirrors in 4 polar orbits at an altitude of 1200 kilometers. They have a 4.0 meter receive mirror and a 6.0 meter transmit mirror.

Figure 20 shows this GBL architecture during a ballistic missile launch from the Korean peninsula. One possible path is GBL1, SB2-4, SB1-4, and finally to SB2-1 where the fighting relay mirror can destroy the missile attack.

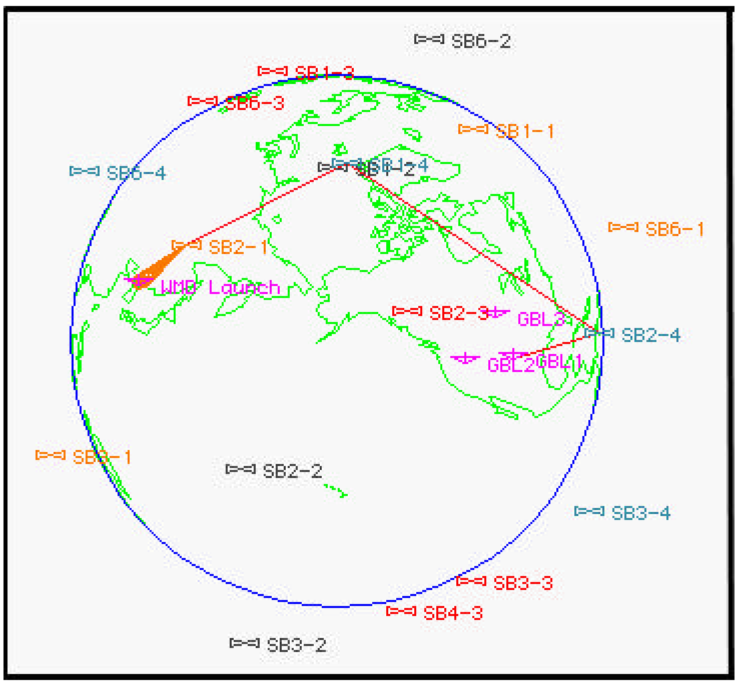

Figure 20. GBL Ballistic Missile Attack

Notes

[1] American Physical Society. *Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons,* (New York, 1987), 187.

Notes

[2] Lawrence Sher, *Optical Concepts for Space Relay Mirrors*. Phillips Laboratory, NM.

[3] American Physical Society, 228.

[4] L.D. Weaver and R.R Butts, *ABLEX: High Altitude Laser Propagation Experiment*, (Phillips Laboratory, Kirtland AFB, NM, Aug 1994), 2.

[5] American Physical Society, 188.

[6] Robert Braham, et al., “Ballistic Missile Defense: its back,” *IEEE Spectrum*, (Sept 97), 43.

[7] Weaver, 3.

[8] Ibid., 3.

[9] Braham, 45.

[10] J. A. Accetta, and D.L. Shumaker, *The Infrared and Electro-Optical Systems Handbook*, (Environmental Research Institute of Michigan: SPIE Optical Engineering Press, 1993), Volume 2, 305.

[11] Ibid., 309.

[12] Ibid., 305.

[13] D.P., Crawford, et al., *Ground Based Laser Atmospheric Propagation Analysis – The Omega Code*, SPIE Vol 1221, Propagation of High-Energy Laser Beams Through the Earth’s Atmosphere, 1990, 145.

[14] Daniel G. Fouche, et al. “Scaled Atmospheric Blooming Experiments (SABLE),” *The Lincoln Laboratory Journal*, Volume 5, Number 2, (1992), 287: Figure 9.

Appendix G

ABL w/Relays Architecture Design

The concept for a ABL with Relay Mirrors boost-phase NMD is very similar to the GBL architecture except for two major differences. The first is that with Airborne Laser, only one laser source is required because the ABL flies above the weather that might interfere with laser firing. The second difference is that because the ABL is operated from an airplane, it has limited laser power which limits the number of ballistic missile kills that the architecture can achieve.

The concept starts out simpler than the GBL with Relay Mirrors architecture. Since the ABL will fly at 12.9 kilometers altitude and this is above the clouds,[1] it would take only one operational ABL flying in the US to guarantee that weather would not prevent it from providing the NMD laser power when required. The NMD allocated ABL would fly an operational track in the United States, or for that matter anywhere in the world. It would have direct access to the Relay Mirror architecture as it flies above the clouds. Worldwide access, by the relay mirror satellites, to attack the ballistic missile threats has already been demonstrated in earlier Appendices. This relay arrangement along with the ABL flying an operational track in the US, is depicted in Figure 21.

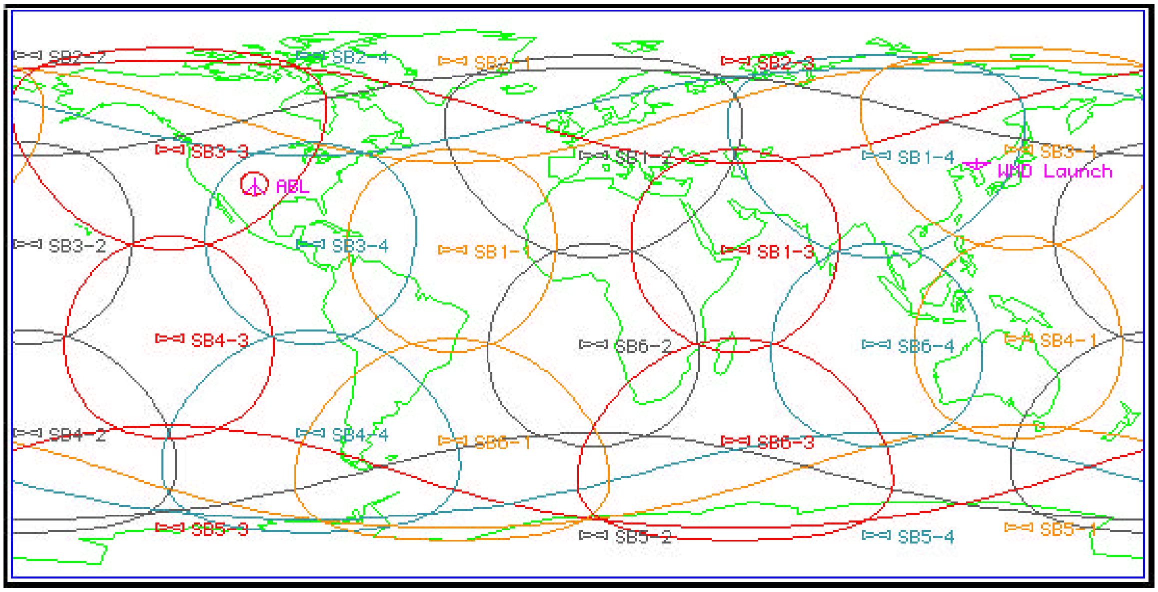

Figure 21. ABL Architecture

In order for the Relay Mirror Satellite to receive the laser from the ABL, its receive aperture must be large enough to capture the laser beam. The receive aperture must be sized to receive the laser from the maximum relay range of 4082 kilometers.

$$\text{Dreceive} = 2.44 \times \text{Range} \times \lambda(\text{laser wavelength})/\text{Dtransmit}$$

$$= 2.44 \times 4{,}082{,}000 \text{ meters} \times 1.3\times 10\text{^-6 meters}/2^2 \text{ meters}$$

$$= 6.5 \text{ meters}$$

Because of the overlap in Relay Mirror coverage, the ABL might have more than one option about the relay satellite it wants to use for the ballistic missile attack. This is depicted in Figure 22.

Once the laser is passed through up to 4 relay satellites, the laser can be focussed on the ballistic missiles. Unfortunately the ABL architecture quickly runs into technology problems for achieving the critical 600 Watts/cm^2 on the ballistic missile skin like the other boost-phase options. The ABLs combination of low power (3 MW[3]) and small transmit aperture (2 meter diameter[4] is the best quoted value – some articles say 1.5 meters) limit this boost-phase option.

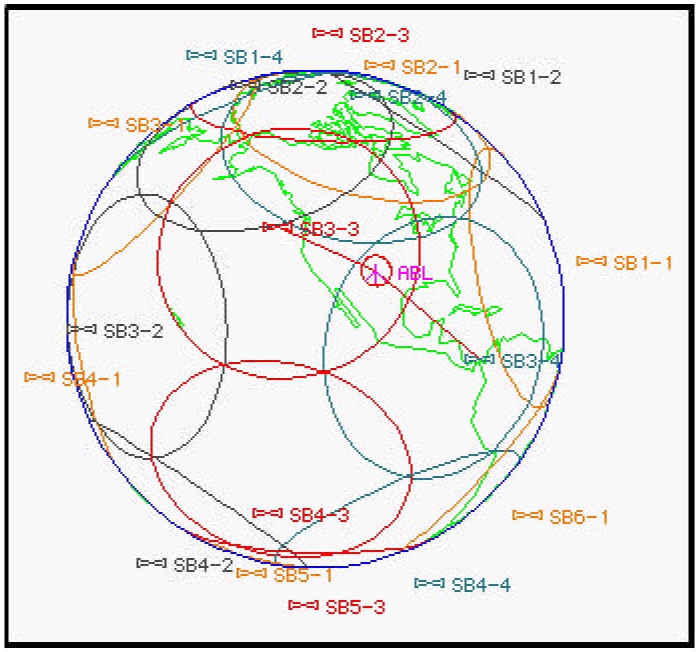

Figure 22. ABL Access to Multiple Relay Satellites

The ABL has similar architecture and atmospheric losses to those discussed in Appendix F for GBL. The atmospheric losses for ABL during the ABLEX experiments show its minimum Strehl ratio to be .75[5] while firing horizontally. However since ABL will be firing vertically in this architecture, the Strehl ratio should be higher because the atmosphere is less turbulent.[6] ABL Strehl ratios should even be slightly better than GBL efficiencies because the ABL has less atmosphere to fire through (assumed .95 verses .92 for GBL). Additionally, the architecture efficiencies are still 80% for every relay transition. Therefore, the final laser power transmitted from the attacking relay mirror is:

Ptrans = Pabl × [(Architecture losses) × (Atmospheric losses)]

= 3MW × [(.8 ×.8 × .8 × .8) × (.95 × .95)]

= 1.1 MW

Thus the 3 MW laser transmitted by ABL has dwindled to 1.1 MW. To achieve the required NMD brightness, the transmit mirror of the attacking relay mirror would have to be increased to:

$$D_{transmit} = [1.2 \times \lambda^2 \times B(\text{required brightness})/P\ (\text{laser power})]^{.5}$$
$$= [1.2 \times (1.3\times10^{-6}\ m)^2 \times 10^{20}\ \text{Watts/steradian} / 1.1 \times 10^{6}\ \text{Watts}]^{.5}$$
$$= 13.5\ \text{meters}$$

This means that to guarantee that the ABL system will have the correct brightness to satisfy the NMD requirements all the time, would require using a 13.5 meter transmit aperture on the fighting relay mirrors. This is out of even BMDO's capabilities for the near future as discussed in Chapter 5. If the relay transmit apertures were 11 meters (the largest that BMDO has demonstrated), it would require an ABL with laser power of 4.5 MW. ABLs planned improvements such as "advanced COIL, adaptive optics, and beam control technology [will] provide a 20-30% increase in ABL operational range"[7] in the next 6 years. Therefor this 50% improvement of laser power seems aggressive but doable in the future. However, even without these improvements the ABL as designed today could kill a significant number of ballistic missiles.

Using an assumed 3MW, 2 meter aperture ABL and the relay architecture with an aggressive 11 meter transmit aperture, the attacking relay mirror's brightness is:

$$\text{Brightness} = P \times D^2/(1.2 \times \lambda^2)$$
$$= 1.1 \times 10^{6}\ \text{Watts} \times (11\ \text{meters})^2/[1.2 \times (1.3\times10^{-6}\ m)^2]$$
$$= 6.6^{19}\ \text{Watts/steradian}$$

This means that the time to kill the ballistic missile is:

$$\text{Time to Kill} = (\text{Max range})^2 \times \text{Booster Hardness/Laser Brightness}$$

= (4,082,000 meters)² × 24,000,000 Joules/m² /6.6^19 Watts/steradian

= 6 seconds

Using the time formulas developed in Appendix B, this means that this ABL with Relay mirror architecture could kill:

Missiles Killed = (120 secs – 10 secs acq.)/(1.5sec slew + 6 sec kill)

= 14

Therefore, an ABL as designed with a Relay Mirror architecture implemented could kill 14 ballistic missiles launched simultaneously. The Relay Mirrors would have to have a 6.5 meter receive aperture to receive the ABL beam and an aggressive 11 meter transmit aperture to achieve these 14 kills in 2 minutes. Figure 23 shows one of the possible paths (ABL to SB3-3 to SB3-1) as this ABL with Relay Mirror architecture attacks the ballistic missile launch from the Korean peninsula.

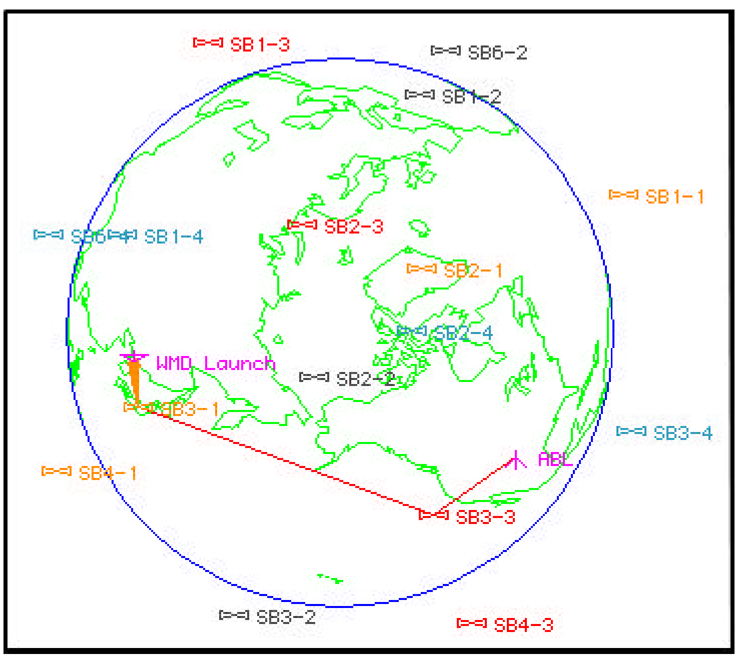

Figure 23. ABL Attack on Ballistic Missiles

Notes

[1] Robert Braham, et al., "Ballistic Missile Defense: its back," *IEEE Spectrum*, (Sept 97), 42.

[2] L.D. Weaver and R.R Butts, *ABLEX: High Altitude Laser Propagation Experiment*, (Phillips Laboratory, Kirtland AFB, NM, Aug 1994), 16.

[3] Braham, 43.

[4] Weaver, 16.

[5] Weaver, Figure 14.

[6] Braham, 46.

[7] Office of Naval Research, *Chapter X – Weapons*, *Defense Technology Area Plan*, http://www.dtap.com.

Appendix H

Flexible Relay Mirror Architecture Design

A flexible relay satellite architecture that could be supplied laser power by multiple laser inputs could be designed by looking at all the previous designs in tandem. The relay satellites would obviously be in the same 24 satellite configuration as in the other architectures which would provide worldwide coverage for attack on enemy ballistic missiles.

The receive mirrors on these relays would be driven by the beam size of the Airborne Laser. It was shown in Appendix F, that this requires a receive aperture on the order of 6.5 meters. This allows the GBL to also transmit to the constellation, but the SBL design will have to be modified slightly. If we keep the SBL sources in the same 5200 kilometer equatorial orbit, their transmit aperture would have to be increased in size so that the laser can be captured by a 6.5 meter receive mirror.

Dtrans = 2.44 $\times$ Rmax $\times$ λ laser / Dreceive

Dspot = 2. 44 $\times$ 13,837,000 meters $\times$ (1.3 $\times$ 10^-6 meters)/ 6.5 meters = 6.8 meters

Thus if the SBL increased its transmit aperture to 6.8 meters (vice 6 meters), it could also feed the same relay satellite architecture fed by both ABL and GBL. This effect could generated by lowering the orbit of the SBL satellite and increasing its power to overcome larger architectural efficiencies.

To minimize the complexity of this Flexible Relay Mirror architecture, the transmit aperture will be kept at 6 meters, the same as the GBL and SBL with Relay Mirrors' architectures. This means that any boost-phase systems supplied laser power by these sources could kill 20 enemy Taepo Dong 2 missiles in the NMD 2 minute timeline. However the ABL would not be able to kill this many because of low transmitted laser power. The maximum number of missiles that only the ABL could kill would be:

ABL Brightness $= P \times D^2/(1.2 \times \lambda^2)$

$= 1.1 \times 10\text{^}6 \text{ Watts} \times (6 \text{ meters})^2/[1.2 \times (1.3\times10\text{^-}6 \text{ m})^2]$

$= 1.95\text{^}19 \text{ Watts/steradian}$

Therefore the time to kill one ballistic missile at maximum range is:

Time to Kill = (Max range)^2 $\times$ Booster Hardness/Laser Brightness

= (4,082,000 meters)^2 $\times$ 24,000,000 Joules/m^2 /1.95^19 Watts/steradian

= 20.5 seconds

Using the time formulas developed in Appendix B, this means that this ABL with the Flexible Relay Mirror architecture could kill:

Missiles Killed = (120 secs – 10 secs acq.)/(1.5sec slew + 20.5 sec kill) = 5

Thus we can see the beauty of this Flexible Relay Mirror architecture. It is a lower risk system, that could be supplied laser power from different sources depending on the situation. If it were implemented, a single ABL could kill a minimum of 5 enemy ballistic missiles in the boost-phase. A single GBL site would have a 70% chance (due to weather – see Appendix F) of killing a minimum of 20 ballistic missiles. Additional GBLs or SBLs could be added as requirements increased.

Glossary

ABL	Airborne Laser
ACSC	Air Command and Staff College
ALI	Alpha/Lamp integration, end-to-end test operation of SBL
Alpha	SBL test HF Chemical Laser built by BMDO
ASAT	Anti-satellite
ATP	Acquisition, Tracking, and Pointing
ATP/FC	Acquisition, Tracking, Pointing and Fire Control
AU	Air University
BMD	Ballistic Missile Defense
BMDO	Ballistic Missile Defense Organization (USAF)
COIL	Chemical Oxygen Iodine Laser
DEW	Directed Energy Weapons
DF	Deuterium Fluoride laser
DOD	Department of Defense
FEL	Free Electron Laser
GBL	Ground Based Laser
HEL	High Energy Laser
HELSTF	High Energy Laser System Test Facility (White Sands Missile Range, NM)
HF	Hydrogen Fluoride laser
HPL	High Power Laser
IR	Infrared
Kj	Kilojoule (1000 joules or 1000 Watt seconds)
LAMP	Large Advanced Mirror Program
Laser	Light Amplification by Stimulated Emission of Radiation
LOS	Large Optical Segment: produced one segment of an eleven meter diameter mirror
MAD	Mutually Assured Destruction

µm	micrometer (.000001 meter)
MIRACL	Mid Infrared Advanced Chemical Laser at HELSTF
MW	Megawatt (1000 Watts)
NASA	National Aeronautics and Space Administration
NGST	Next Generation Space Telescope
NIE	National Intelligence Estimate
NMD	National Missile Defense
NSS	National Security Strategy
O&M	Operations and Maintenance
OTA	Office of Technical Assessment
RDT&E	Research, Development, Test and Evaluation
RME	Relay Mirror Experiment
SBL	Space Based Laser
SHIELD	System High Energy Laser Demonstration, integrated ground test of SBL and ATP
SOAP	Satellite Orbit Analysis Program (Aerospace Corporation)
Strehl Ratio	Percentage of main laser lobe that arrives on target
TMD	Theater Missile Defense
USSPACECOM	US Space Command
USSR	Union of Soviet Socialist Republic

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