

AIR WAR COLLEGE

AIR UNIVERSITY

HARNESSING LIGHT:
LASER/SATELLITE RELAY MIRROR SYSTEMS
AND DETERRENCE IN 2035

by

Michael J. Stephens, Lt Col, USAF

A Research Report Submitted to the Faculty

In Partial Fulfillment of Graduation Requirements

16 February 2010

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BIOGRAPHY

Lieutenant Colonel Michael J. Stephens was commissioned in the U.S. Air Force after graduating from the U.S. Air Force Academy in May 1989. As a career developmental engineer and acquisition officer, he has served in assignments in laboratory, program office, and flight test organizations. He also served as a plans and programs staff officer at the Pentagon, as well as commanding the 344th Recruiting Squadron in Arlington, TX. In early 2009, he deployed to Camp As Sayliyah, Qatar, for Special Operations Command–Central in support of ongoing operations in Iraq and Afghanistan. He entered Air War College as a student in July 2009. Lieutenant Colonel Stephens holds a Bachelor of Science degree in Aeronautical Engineering from the U.S. Air Force Academy, a Master of Business Administration degree from the University of West Florida, a Master of Science degree in Aeronautical Engineering from the Air Force Institute of Technology, and is a graduate of the Advanced Program Manager's Course at the Defense Systems Management College. He is also a graduate of the Flight Test Engineer program at the U.S. Air Force Test Pilot School, with over 600 flight test hours as a crewmember in over 36 different aircraft, primarily the F-15, F-16, and E-8C.

I. INTRODUCTION

Directed energy weapons represent a potential revolution in military capabilities for tomorrow's warfighters. Lasers are already used for making precise measurements, cutting, communications, and power transmission. At higher power levels, lasers have the potential to be formidable weapons, both lethal and non-lethal. In recent years, the U.S. has made several advances in high-powered laser technology, producing a megawatt-class laser, with several other countries not far behind.¹

Combining lasers with space-based relay mirrors could offer the capability of transmitting a ground-based laser toward any point on the earth, an orbiting satellite, or a ballistic missile in flight. By the year 2035, several nations will likely have developed this capability, which will significantly affect U.S. national security. This paper examines the threat posed to the U.S. by a laser/relay mirror system and addresses the issue of how the U.S. should deter hostile nations from employing such a system.

This paper starts by describing current laser technology and the lethality effects of high-powered lasers. A description of a space-based relay mirror system follows, along with a description of technical challenges for implementation and threats posed by such a system against U.S. ground, air, and space systems. The paper concludes with a brief discussion on deterrence theory and recommends on how the U.S. should posture itself to deter adversaries who develop and employ a laser/relay mirror system.

II. DESCRIPTION OF LASER TECHNOLOGY

In basic terms, a laser is created when coherent light waves interact in such a way as to form “excited” atoms creating a beam of electromagnetic radiation (Figure 1).² The beam is formed when a group of excited atoms is energized by an outside power source through creation of a chemical reaction (chemical oxygen-iodine laser), an electric discharge, or flashlamp (ruby laser).³ The distinguishing characteristic of a laser beam is the way the beam remains relatively intact, in a tight cylinder, for extremely long distances. The beam is affected by the stability of the optical platform (called “jitter”), power fluctuations, impurities in the lasing medium, and atmospheric conditions between the source and the target. The ability to direct large amounts of energy accurately, near-instantaneously to a small spot from extremely long distances opens up a new range of possibilities for military use.⁴

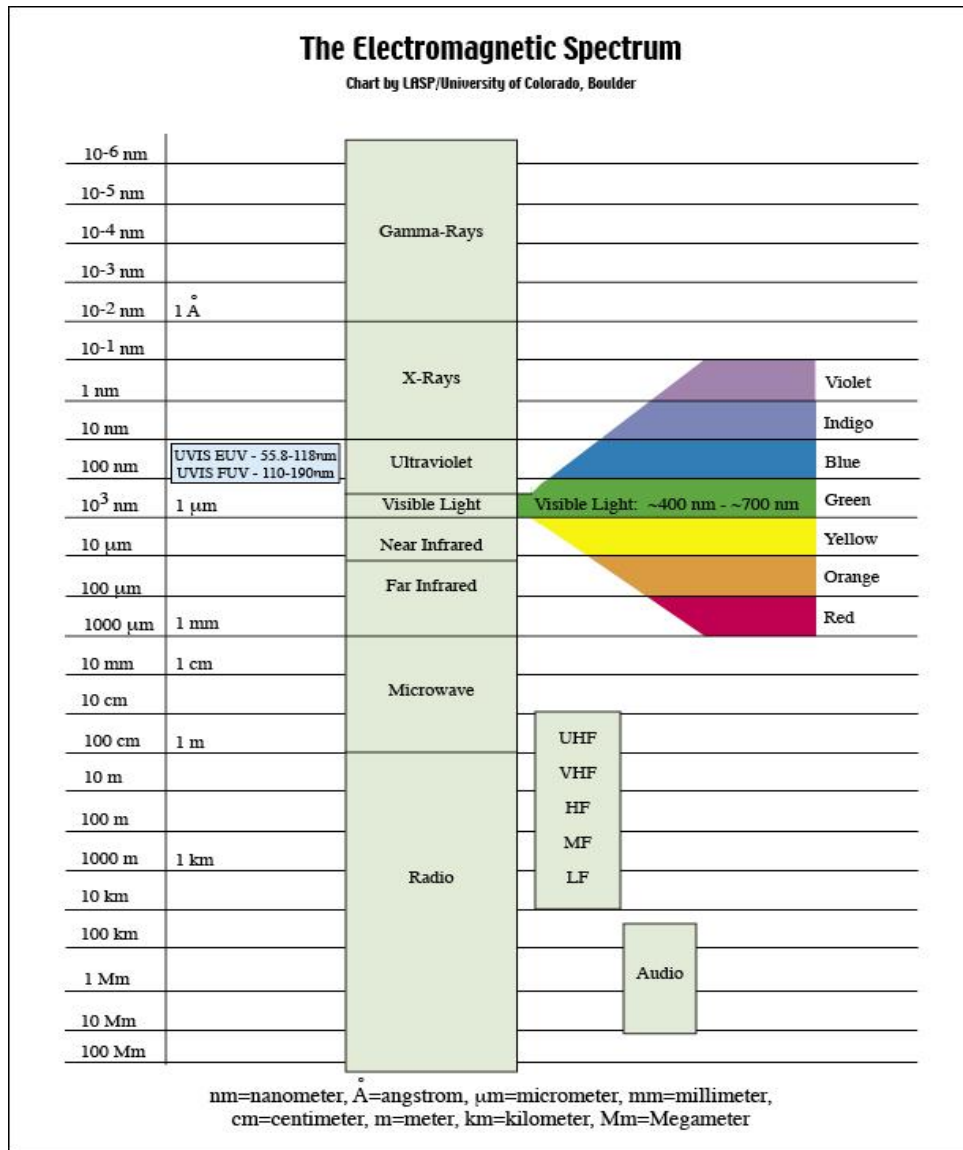


Figure 1. Electromagnetic Spectrum

Types of Lasers

In addition to chemical lasers currently in use, there are three types of lasers which are the most likely candidates to produce sustainable megawatt-class laser beams required for military utility.⁵ They are listed below:

Free electron lasers – these types of lasers are classified as electric lasers and can be designed to illuminate any wavelength or frequency, from gamma rays to microwaves. Each free

electron laser is also tunable, able to change frequencies within a limited range centered on the frequency for which the laser was designed.⁶ Free electron lasers produce radiation by sending fast electrons through a magnetic field, typically a series of alternating magnets.⁷ Figure 2 shows a diagram of a free electron laser.⁸

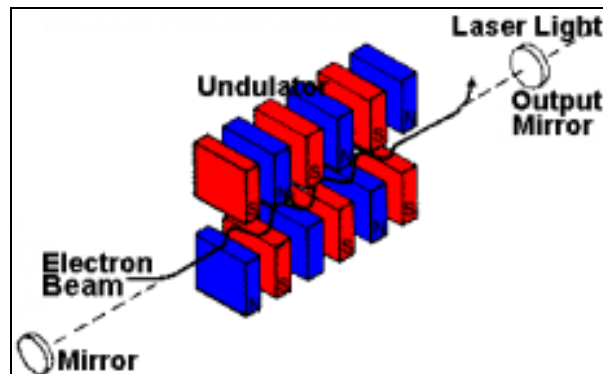


Figure 2. Free Electron Laser Diagram

Fiber lasers – these types of lasers are produced by injecting light into a super-thin optical fiber containing an amplifying medium. Since there is a limit to the power produced within each fiber strand, these strands can be bundled to produce a laser with a higher combined power output.⁹

Solid state lasers – these types of lasers excite molecules inside a crystal solid until they can be induced to return to a lower energy state in unison. They tend to generate a great deal of heat that must be dissipated, which is a current limitation for this type of laser.¹⁰

Lethality Effects of Lasers

The primary effect caused by a laser is heating, caused by the target surface absorbing the beam's energy.¹¹ A laser's damage potential is measured in terms of fluence, or energy per unit area (Joules/cm²). For high-energy laser weapon applications, such as anti-ballistic missile defense or anti-tank applications, a fluence of 10,000 Joules/cm² is considered the minimum

required. This corresponds to a laser with a power of approximately one megawatt.¹² If the laser dwells on a target long enough, it can cause melting and vaporization of metal. For example, the U.S. Air Force's Advanced Tactical Laser program is essentially a scaled-up version of a laser cutting tool. In October 2009, this C-130 fired a laser at a truck on a test range, burning a hole in the vehicle's front hood and into the engine.¹³ If the laser power were scaled up further, the result could be a formidable battlefield weapon.

In addition to thermal and vaporization effects, lasers can have a devastating effect on human beings. A threshold of approximately 15 Joules/cm² is all that is required to burn human skin, and less than 1 Joule/cm² causes permanent eye damage.¹⁴ A high-energy laser shot would severely burn or vaporize a human being, but even reflected laser energy can still blind a person and cause corneal burns or retinal damage.¹⁵ A high-energy laser pulse can be reflected in the vicinity of any people in the target area, often without their immediate knowledge. High-energy military lasers are often not in the visible portion of the electromagnetic spectrum, which makes it extremely difficult for people to actively avoid collateral eye damage from laser beams.¹⁶

III. DESCRIPTION OF A GROUND-BASED LASER/SPACE-BASED RELAY MIRROR SYSTEM

A laser/space-based relay mirror system greatly enhances the range and lethality of laser weapons. This paper will focus on a high-energy ground-based laser with satellite relay mirrors, a concept demonstrated in principle between two mountains in 1983.¹⁷

Ground-Based Laser

The primary driver behind the lethality of this system is a high-powered, ground-based laser pointed toward the orbiting relay mirrors. Although there are several types of high-powered lasers currently in development, including the ones described in Section II, all of them face the challenge of being able to produce a beam with power in the megawatt range. Using a ground-based laser instead of a space-based or airplane-carried laser greatly simplifies logistics and power production, which is a significant advantage. Theoretically, only one ground laser is required, but multiple sites can be built to ensure redundancy for the nation during a conflict.

The defining characteristics of this type of system are beam power and coherence. In order to achieve the minimum 10,000 Joules/cm² on a ground target, studies indicate that a minimum power output of approximately 1.4 megawatts would be required for an effective missile defense system, based on an assumption of 25 percent cumulative losses due to atmospheric effects to and from the relay mirrors, absorption, and jitter.¹⁸ However, Air Force Research Laboratory (AFRL) plans include a goal of four to ten megawatts for a U.S. system.¹⁹ As a laser beam travels from the ground to outer space, it encounters moisture, pressure, and density changes in the atmosphere, all of which contribute toward unfocusing the laser beam by the time it reaches the satellite relay mirror. An adaptive optics system is a feedback mechanism that allows the initially distorted beam to be fed back to the laser source, where a computer algorithm can determine how to compensate for the distortions. To correct these distortions, a

computer makes thousands of small deformations in the laser's optical mirror in such a way that the laser beam is deliberately distorted prior to being shot through the atmosphere. The atmosphere then acts as a lens, refocusing the beam to a coherent point at the relay mirror.

Figure 3 shows a schematic of an adaptive optics system.²⁰

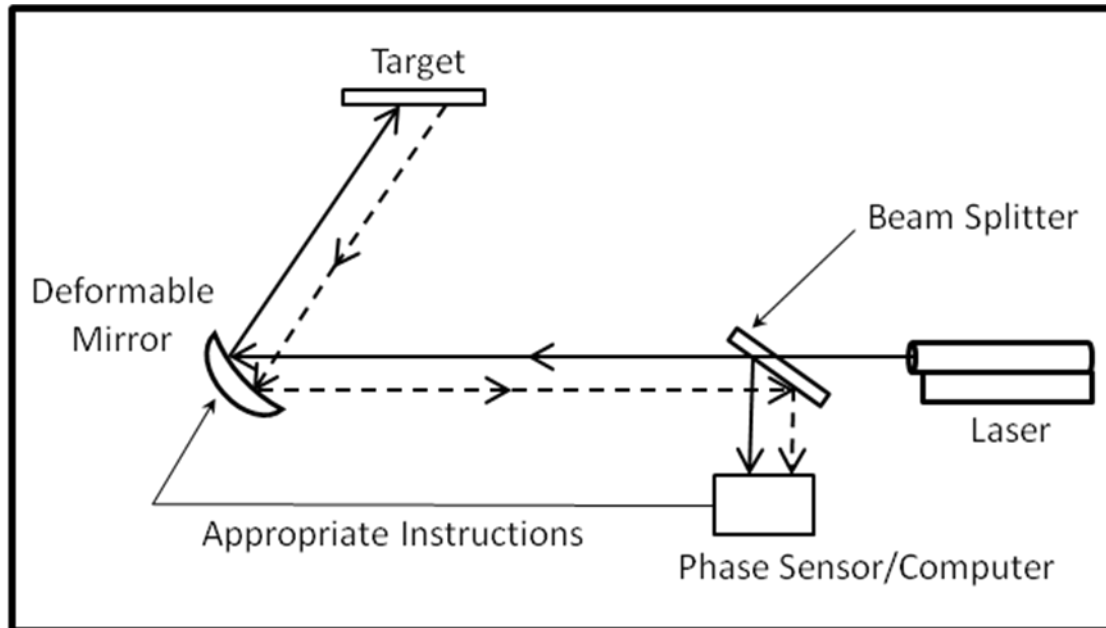


Figure 3. Schematic of an Adaptive Optics System

Relay Mirror Satellites

The relay mirror satellite system is the enabling part of the system that allows the power of the laser to be extended worldwide. The satellite itself consists of a standard satellite bus, including small rocket motors for attitude/position control, a cooling system, attitude gimbals, and a central computer. The relay mirrors would be mounted on the outside of the satellite and would likely be between three and eight meters in diameter, depending on design.²¹ For worldwide coverage, at least four satellites would be required if placed in geosynchronous orbit

(40,000 kilometers above surface of earth), or twenty if placed in low or medium orbit (4,000 kilometers above surface of earth).²²

The key to the laser/relay mirror system functioning properly is the design of the mirrors. There are two primary types of mirrors to be considered: a monacle mirror and a bifocal mirror (see Figure 4). A monacle mirror receives a laser beam and refocuses it toward a target with the same mirror. A bifocal mirror, or binocular system, has two lens systems, with the laser beam passing through the first aperture to be “conditioned” to correct atmospheric distortions. The beam is then amplified with a chemical or solid-state amplifier, and then refocused on to the target through the second aperture.²³ The binocular system is more complex, but is a more accurate system and is better at refocusing the beam to create maximum fluence on the target.

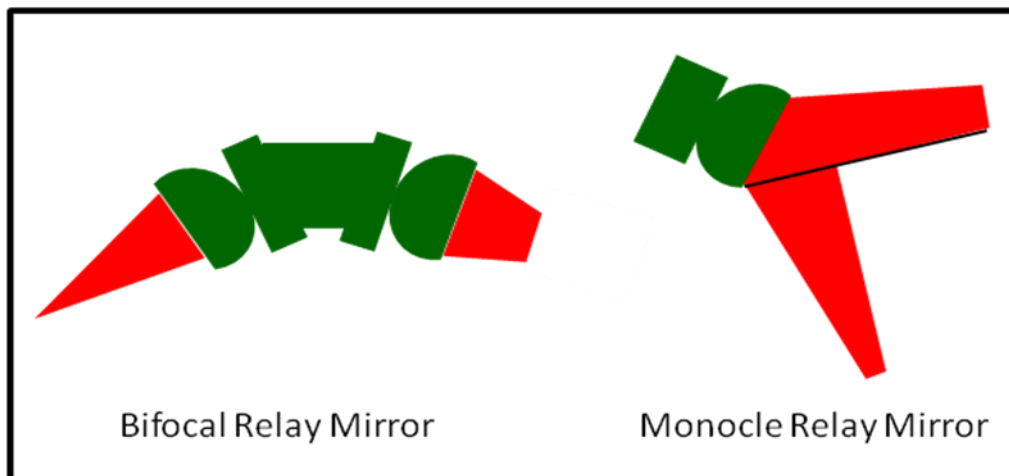


Figure 4. Bifocal vs. Monocle Relay Mirror

Figure 5 shows a schematic of a laser/relay mirror system with a laser beam originating from the ground and being re-directed from one relay mirror to another, then to a ground target on the other side of the world from the originating beam. The capability to instantaneously hit a target anywhere on the planet with a potentially lethal laser beam would be a dramatic leap in

technology. With relay mirror satellites in orbit in appropriate locations, a beam could be directed to any ground point on the planet.²⁴

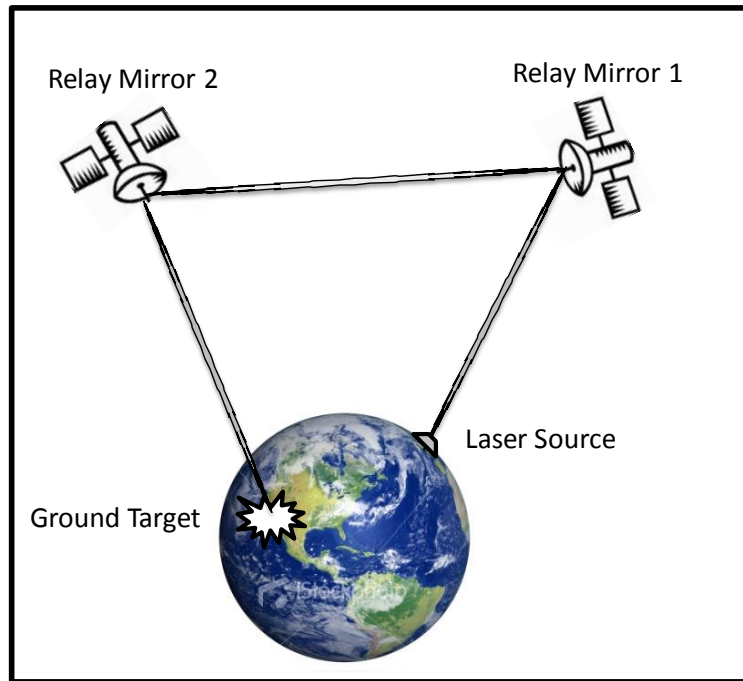


Figure 5. Laser/Relay Mirror System Engaging Ground Target

Figure 6 shows a schematic of a laser/relay mirror system with a laser beam originating from the ground and being re-directed from a relay mirror toward an enemy satellite. With the U.S.' heavy reliance on satellites for a variety of uses, this is also a significant vulnerability. Instead of pointing the beam at another orbiting satellite, the beam could also be directed at a missile or airplane in flight.

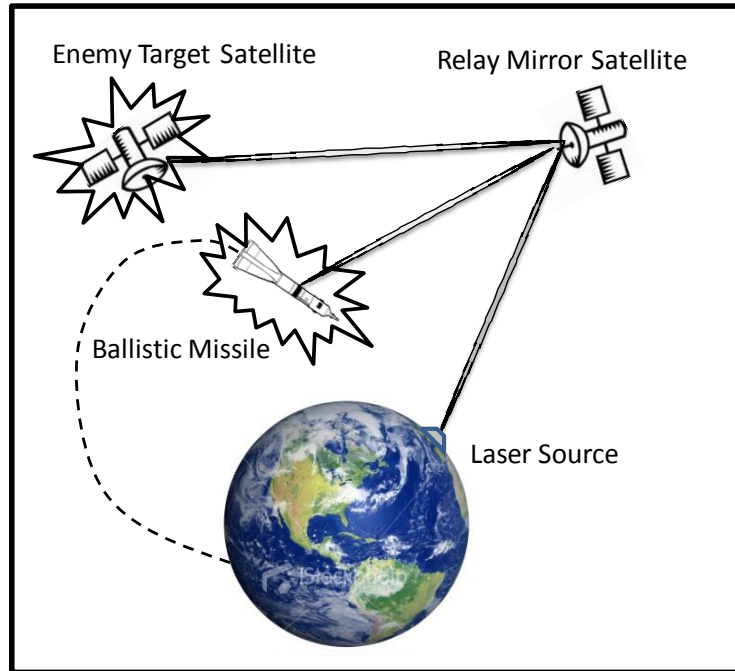


Figure 6. Laser/Relay Mirror System Engaging Space Targets

Technical Challenges

The original premise of this paper was addressing the question of how the U.S. should posture itself to deter a potential adversary using a laser/relay mirror system in 2035. The areas listed below outline the primary areas of emphasis:²⁵

Ground-Based High-Powered Laser – There is still much research and testing to be accomplished in order to build a reliable, repeatable, possibly mobile, megawatt-class ground laser. Technology areas requiring further breakthroughs include optical lens and mirror materials, optical alignment, power generation and transmission, and thermal management.²⁶

Satellite Vehicle/Relay Mirror Design – A relay mirror satellite will be different from other satellites in that its ability to stay pointed in a particular orientation is critical. Not only does the satellite itself have to be able to remain orientated properly, but the relay mirror has to be able to make microscopic precision movements in order to redirect the laser beam in the

proper direction. In order to accommodate the high-powered laser beams without melting, advances are required in optical coating materials for the relay mirrors.²⁷

Vibration and thermal management, attitude and jitter control, and slewing all require additional research. Vibration must be controlled because the laser must point precisely at the target. Vibration and material expansion due to heat buildup need to be addressed in satellite design. Controlling the satellites' attitude and motion is needed to ensure exact orientation toward the target and the incoming beam, which is necessary for relaying the laser toward its aim point. Lastly, slewing and momentum control present challenges, as once a satellite rotates to orient itself toward a target, the satellite must be able to stop its angular momentum.²⁸

Acquisition/Tracking/Targeting Algorithms – This is an area of critical importance that brings the entire system together. First, the ground laser must be able to detect and track the first relay mirror satellite. If the target is not within line-of-sight of the first relay mirror, the beam must be directed to a second relay mirror. At the end of the line, the target, which itself may be moving (missile or airplane), must be detected, tracked, and targeted. All of this detection, tracking, and targeting must be accomplished simultaneously. The 1991 Gulf War saw the “transformation” of reducing the targeting “kill chain” from hours to minutes. This system will further reduce the timeline from minutes to seconds from target identification to target engagement.²⁹

IV. EFFECTS OF A LASER/SPACE-BASED RELAY MIRROR SYSTEM ON U.S. GROUND, AIR, AND SPACE SYSTEMS

Based on the aforementioned transformational capabilities offered by a laser/relay mirror system, such a system would represent a grave threat if used against the U.S. Given the fact that the basic technology exists today, and a successful demonstration of the concept was accomplished 27 years ago, it is likely that a U.S. “near-peer” competitor—especially China and Russia—could field this technology by 2035. If that is the case, what are the implications for the U.S.?

From a military standpoint, lasers represent a potent threat to ground, air, and space equipment. An estimated 10 Joules/cm² is required to damage optical sensors and radomes; 700 Joules/cm² is required to punch a hole in an aircraft’s skin; and approximately 5,000-10,000 Joules/cm² would be required to disable or destroy an aircraft.³⁰ The vulnerability of several types of military equipment to lasers is detailed below:

Satellites – A relatively low damage threshold makes most satellites vulnerable, as the vast majority of military and commercial satellites are built with weight being minimized as a design driver. Even a brief laser hit in one of the sensors or an antenna could render the satellite useless. A hit to one of the rocket motors or a gyro would cause its attitude control system to become inoperative. A hit to a solar panel, battery, or primary electronics section could cause the satellite to go “dark” or malfunction permanently.

Aircraft – An airplane’s most vulnerable areas are the wings and the cockpit. A hole punched in a wing could lead to fuel ignition and cause a crash. The wings also contain hydraulic lines leading to the flight control surfaces. If these lines were severed, this could also cause the aircraft to crash. The cockpit is vulnerable, as all of the computing equipment and

displays are located there, but the biggest threat is to the pilots themselves. It takes very little laser energy to permanently damage the human eye, cause blindness, or kill the operators.

Missiles – The original idea for the laser/satellite relay mirror system originated from the Strategic Defense Initiative program, which had a goal of defending the U.S. from enemy intercontinental ballistic missiles (ICBMs). An ICBM is basically vulnerable in two areas. The guidance, navigation, and control section is located in the nose section of the missile and is susceptible to having its position and targeting information disrupted by a laser shot. The bulk of the missile is made up of a liquid or solid fuel tank, which if penetrated by a laser, could cause the tank to explode in flight. Atmospheric cruise missiles have similarly-shaped bodies with the same vulnerability areas as an ICBM, but since they have low-altitude flight paths and typically low-profile radar cross-sections, it becomes a tracking challenge—but not an insurmountable one—for the laser/relay mirror system.

Tanks/Armored Vehicles – Tanks and armored vehicles are one of the categories of equipment least likely to be affected by lasers. Their thick metal structure is not likely to be penetrated unless the laser has a substantial dwell time—not impossible, but more of a challenge. Even if the structure is not penetrated, “soft” spots, such as treads, tires and areas between moving parts could be affected, resulting in a mission “kill,” even if the occupants survive. As with airplanes, it is possible for the laser energy to enter the occupant cabin and cause eye damage to the soldiers.

Trucks/Jeeps/Automobiles – These types of ground vehicles are vulnerable to lasers because of the relatively thin metal on their roofs and their open design, with large passenger windows. A high-energy laser beam could quickly explode or disable a vehicle.³¹

Threats Posed by Potential Adversaries

As “near-peer” competitors to the U.S., China and Russia have demonstrated the capability and willingness to dominate the outer space environment, as well as use lasers as a battlefield weapon. While not facing an immediate threat from a laser/relay mirror system, U.S. military strategic planners have to consider the worst-case future scenarios.

There are several relevant incidents which should give one pause when considering how the U.S. should position itself in the long-term future from a military standpoint. There were reports of Soviet lasers used against Chinese troops during the conflict between China and Vietnam in the late 1970s.³² Russia launched several “interceptor” satellites in 1976-77, which proved its capability to place a satellite in a precise location. In a conflict, this could ultimately be a kinetic energy anti-satellite (ASAT) weapon, or a way to put a jamming satellite close to a U.S. satellite.³³ Russia continued its ASAT activities after the end of the Cold War, with space launches testing new satellite interception techniques. Among these activities was the test of a MiG-31 fighter aircraft carrying an ASAT missile in 1992³⁴ and its conduct of a high-altitude electromagnetic pulse (EMP) test in 1999.³⁵ In addition, Russia has developed ground-based lasers with a lethal range of 287 miles, with damage-causing capability out to 460 miles, putting low-earth orbit satellites at risk.³⁶ China launched a missile and destroyed one of its own weather satellites in January 2007.³⁷ It has been developing lasers specifically with an anti-satellite mission.³⁸ All of these incidents indicate that the U.S. needs to be prepared to meet any future threat, especially when it comes to directed energy weapons and space control.

On the civilian side, the threat is ultimately worse. In a worst-case scenario, a perfected high-energy laser beam could be used to destroy all U.S. Global Positioning Satellites (GPS) and communications satellites in short order. That would disrupt the U.S. banking system, phone

system, and air transportation system, among others. If lasers were used against civilian ground targets, the beam could disrupt electrical grids, disable cars, trains, and airplanes, not to mention blinding, injuring, or killing countless numbers of people in its path. It is clear that this is not a weapon system of which U.S. wants to be on the receiving end.

Legal Considerations

The idea of a laser/relay mirror was created during the Strategic Defense Program of the 1980s and created considerable controversy with respect to two primary arms control treaties.³⁹ The 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies (“Outer Space Treaty”) appears to restrict lasers in space, but the specific wording only refers to nuclear weapons in space.⁴⁰ The 1972 Anti-Ballistic Missile (ABM) Treaty contained language that would restrict high-energy lasers from space use, but the G.W. Bush administration unilaterally withdrew from this treaty in 2002.⁴¹ A laser/relay mirror system extends the debate over the militarization of space, but it might not be as controversial if the defensive aspects are emphasized, such as the missile defense mission. Emphasizing the offensive laser attack or satellite attack capabilities, however, will likely meet stiff resistance from some quarters.

V. HOW SHOULD THE U.S. DETER NATIONS DEPLOYING LASER/SPACE-BASED RELAY MIRROR SYSTEMS?

Deterrence Theory

Before recommending how the U.S. should deter potential adversaries from using a high-energy laser/relay mirror system against it, it is necessary to outline some basic deterrence theoretical concepts. Deterrence, according to T.V. Paul, “is achieved if and when a potential attacker, fearing unacceptable punishment or denial of victory, decides to forgo a planned offensive.” To succeed, a stated threat must be credible, the deterrer must have the capability to deliver on his threat, and he must be able to communicate the threat to his opponent. Finally, all of the actors involved are assumed to be rational (not suicidal).⁴² According to Emmanuel Adler, “deterrence by denial” is the idea of not allowing an adversary to have the capacity to commit successful aggression. “Deterrence by punishment” is dissuading an adversary from using force by making it more costly for him to engage in unwanted behavior.⁴³ Overall, according to Air Force Doctrine Document 2-12, the adversary’s leadership “must be convinced that the cost of aggression against the U.S., its interests, or its allies will be so high as to outweigh any possible gain.”⁴⁴

Recommended Overall Deterrence Approach

After examining the potential effects of laser/relay mirror system, the most prudent approach for the U.S. to take is a “deterrence by punishment” approach. It appears that the U.S., China, and Russia are in another arms race to achieve the capability first, similar to the Cold War. However, as terrible as some of the laser effects are (blindness, for example), this is not a “doomsday” weapon that would kill millions of people with a single push of a button, like a nuclear weapon. This system is designed to be a high-powered scalpel that can disable or eliminate a wide range of targets within seconds of the decision to engage. The transformational

element of this type of weapon system is the compression of time. A high-powered laser would allow one side to attack several targets decisively before the other side has time to prepare or react. Thus, while not quite the same as mutual assured destruction, the applicable deterrence theory is similar if two adversaries have this system. There is no practical way for the U.S. to prevent Russia and China from developing the technology required for a laser/relay mirror system. However, the U.S. can increase its space surveillance capabilities in order to quickly detect the source of a laser attack against a ground target or satellite. Knowing the source of a laser attack would enable the U.S. to rapidly respond appropriately against the attacking country, either conventionally or with a laser attack of its own. Overall, it is incumbent upon the U.S. to develop a laser/relay mirror system first and perfect its operation. When/if other countries catch up to the U.S.' technology, the U.S. will be in a position to inflict grave, hopefully unacceptable, damage to a potential adversary who seeks to use high-energy laser power in conjunction with relay mirrors against U.S. targets or interests.

Countermeasures to a Laser Threat

In conjunction with improving its space surveillance capabilities, the U.S. must develop some countermeasures against a high-energy laser threat. Several of the below countermeasures address meeting the laser threat itself, while others either minimize the threat of laser damage, attempt to avoid it altogether, or quickly deal with the aftermath. Most of these countermeasures would not be effective against a direct high-powered laser shot, but if an enemy dialed down the power or briefly hit a satellite, they might have limited utility.

Real-time space surveillance/laser detection sensors – In most cases, the only way the U.S. would know if a satellite had been attacked with a high-energy laser is by the lack of data received from it. There currently is no space surveillance system in the sense of a satellite using

sensors to monitor its surroundings for threats. Improved space surveillance from ground stations would enable to the U.S. to detect a high-energy laser attack, however—this idea falls squarely into the Department of Defense’s space control mission.⁴⁵ A laser detection system would likely not allow satellite operators time to respond to a high-powered laser attack, but if it was one component of an overall space defense architecture, it could allow the U.S. to quickly figure out where exactly the laser attack originated, and to respond accordingly.⁴⁶

Highly reflective or ablative materials – Ablative materials are those whose top layers absorb heat and flake away when exposed to a high-energy laser beam. The tiles on the nose of the Space Shuttle are an example of this type of material. Ablative materials also sometimes form clouds when heated, which could further absorb or scatter laser energy. Highly reflective materials can alter the thermal/radar signatures of a satellite or ground vehicle.⁴⁷

Laser-resistant materials/Nonlinear optical polymers – Research is ongoing to develop polymers which change properties in the presence of intense lights or electric fields. Such a material would become opaque to laser radiation when hit with a beam, then return to a clear state when the lasing ends.⁴⁸ Research is also ongoing into multilayered graphite material that reflects laser energy instead of absorbing it in the form of heat. This would be extremely useful to protect critical components of satellites.⁴⁹

Shutter Controls – Shutter controls on a satellite would enable the electronics and optical sensors to be protected, either as a precaution at the start of hostilities, or if activated immediately after being hit by a laser beam. By itself, it would not provide absolute protection from a high-energy laser beam, but it would be a prudent precaution, especially if the shutters were constructed out of one of the advanced materials mentioned previously in this section.⁵⁰

Repositioning – Repositioning a satellite might be a futile measure if an adversary has a fully functioning constellation of relay mirrors, but being able to reposition the satellite to face away from the laser beam could buy a bit of time while the beam source is engaged.⁵¹

Redundancy/Quick-launch capability – Another approach to withstanding a laser attack on U.S. satellites is to have spares ready to go at all times. “Families” of satellites might better be able to withstand the loss of one or two satellites of a particular function (for example, the Global Positioning Satellite system).⁵² More efficient launch vehicles and launch systems are needed to cut down on the amount of time between the decision to launch a payload and the payload actually getting into orbit.⁵³ Making the Department of Defense’s plan for Operationally Responsive Space a true reality would strengthen the U.S.’ ability to respond to a laser attack against its space assets.⁵⁴

Cooperation

One other option for the U.S. to pursue in conjunction with deterring its potential adversaries from using technology against it is to look for ways to cooperate. As advances in laser technology are made and are proliferated by various nations, the U.S. could seek ways to use a laser/relay mirror system cooperatively with other countries. One area of particular interest to all space-capable nations is management and tracking of “space junk.” Perhaps there will be an opportunity to use the power of the laser to knock non-functioning satellites and/or debris into a decaying orbit in order to reduce the risk of collisions with future spacecraft and satellites. Two relevant studies indicate the practicality of clearing space debris in low earth orbit with high-powered lasers.⁵⁵

VI. CONCLUSION

“People don’t change when they see the light...they change when they feel the heat.”

– John Smart, Acceleration Studies Foundation⁵⁶

High-energy lasers combined with space-based relay mirrors represent the next revolutionary jump in modern warfare. Such a system offers the capability of transmitting a ground-based laser toward any point on earth, an orbiting satellite, or a ballistic missile in flight. China and Russia have demonstrated the ability and inclination to dominate outer space, as well as use lasers as offensive weapons. By the year 2035, one of them—or another nation—will likely have developed a laser/relay mirror system, which will significantly affect U.S. national security. How the U.S. addresses this future threat and deters hostile nations from employing such a system is a significant challenge.

There are several technical hurdles in laser/relay mirror system design which must be overcome to create an operational system. First, much research is required to build a reliable, repeatable, megawatt-class ground laser, which is the primary driver behind the lethality of the system. Breakthroughs are also needed in adaptive optics, satellite design, and optical coatings for the relay mirrors. Finally, refinements are required in acquisition/tracking/targeting algorithms, which provide the critical link enabling the entire system to find and engage targets.

In the hands of an enemy, the transformational element of a laser/relay mirror system—the compression of time—would allow it to attack several targets decisively before the U.S. has time to prepare or react. With such a concentration of thermal energy, a high-energy laser hit on a satellite could easily burn out its electronics, sensors, and attitude control system. A laser hit on an aircraft could explode a fuel tank and/or blind the pilots. This type of system would also

make an excellent anti-ballistic missile system, with the ability to explode missiles in flight.

Ground personnel—military and civilian—could be vaporized by a direct laser blast or blinded if stationed nearby.

How should the U.S. deter adversaries from deploying such a system against it in 2035?

A “deterrence by punishment” approach in three parts is the most prudent way forward for the U.S. First, the U.S. must improve its space surveillance capabilities, which would allow it to detect a laser attack and pinpoint the source of that attack. Second, the U.S. must implement laser countermeasures for its ground and space systems, such as ablative materials, laser-resistant materials, laser detection sensors, and developing its Operationally Responsive Space capability. Finally, the U.S. must be the world’s first country to develop and perfect a high-energy laser/relay mirror system of its own, which would put it in a position to inflict grave, hopefully unacceptable, damage to an adversary who seeks to use such a system against the U.S.

Overall, ground-based lasers and space-based relay mirror systems are exciting technologies of which the U.S. is just scratching the surface. However, potential adversaries are also making gains in these areas, which represent a threat to U.S. national security if steps are not taken to maintain a technological lead through 2035. The U.S. must invest in the aforementioned laser countermeasures and its own laser/relay mirror system now. It is no longer sufficient to simply count on the U.S. nuclear arsenal to deter other nuclear states from starting an all-out war—lasers will likely soon “change the game” entirely, so the U.S. must be ready.

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Endnotes

¹ Steven Lambakis, *On the Edge of Earth: The Future of American Space Power* (Lexington, KY: The University Press of Kentucky, 2001), 124-25. Also gained knowledge of major “near-peer” capabilities during briefings to Air War College students during tours of Air Force Research Laboratory facilities at Kirtland AFB, NM from 24-28 Aug 2009 and National Air and Space Intelligence Center briefings at Wright-Patterson AFB, OH from 23-24 Sep 2009.

² Doug Beason, *The E-Bomb: How America’s New Directed Energy Weapons Will Change the Way Future Wars Will Be Fought* (Cambridge, MA: Da Capo Press, 2005), 26-27. Figure 1 source: <http://lasp.colorado.edu/cassini/images/Electromagnetic%20Spectrum.jpg> (accessed 6 Dec 2009).

³ Ibid, 60-61.

⁴ The purpose of this paper is not to provide a detailed tutorial on laser fundamentals—only their effects. The reader is referred to the Beason and Nielsen bibliographic references for further details on lasers.

⁵ Defense Science Board Task Force on Directed Energy Weapons, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C., December 2007, 5.

⁶ Beason, *The E-Bomb*, 187-88.

⁷ Michael E. O’Hanlon, *Neither Star Wars nor Sanctuary: Constraining the Military Uses of Space* (Washington, D.C.: Brookings Institution, 2004), 72.

⁸ Source: <http://www.fel.duke.edu/lightsources/> (accessed 18 January 2010).

⁹ Beason, *The E-Bomb*, 200.

¹⁰ O’Hanlon, *Neither Star Wars nor Sanctuary*, 72.

¹¹ Philip E. Nielsen, *Effects of Directed Energy Weapons* (Albuquerque, NM: Directed Energy Professional Society, 2009), 170.

¹² Nielsen, *Effects of Directed Energy Weapons*, 18.

¹³ Rolfsen, Bruce, “Test of Laser from C-130H Melts Hood of Car,” *Air Force Times*, 3 October 2009, http://www.airforcetimes.com/news/2009/10/airforce_tactical_laser_100209w/ (accessed 15 November 2009). The U.S. Navy’s Mid-Infrared Advanced Chemical Laser (MIRACL), located at the White Sands Missile Range in New Mexico, was the first megawatt-class deuterium fluoride, continuous-wave laser, developed in 1980 (Federation of American Scientists, “Mid-Infrared Advanced Chemical Laser (MIRACL),” <http://www.fas.org/spp/military/program/asat/mirac.htm> [accessed 31 October 2009]).

¹⁴ Bengt Anderberg and Myron Wolbarsht, *Laser Weapons: The Dawn of a New Military Age* (New York: Plenum Press, 1992), 115.

¹⁵ Ibid, 68-71.

¹⁶ Edward A. Duff (Long Range Strike Product Line Leader, Air Force Research Laboratory Directed Energy Directorate, Kirtland AFB, NM) in discussions with author, 13 January 2010. Most current high-energy lasers produce beams in the shortwave infrared portion of the electromagnetic spectrum (invisible to naked eye).

¹⁷ Fusion Energy Foundation, *Beam Defense: An Alternative to Nuclear Destruction*, Fallbrook, CA: Aero Publishers, Inc., 1983. Several variations are possible for a relay mirror system, including placing the relay mirrors on an unmanned aerial vehicle, a high-altitude airship (“blimp”), or on satellites. (Duff, discussions with author).

¹⁸ William H. Possel, “Lasers and Missile Defense: New Concepts for Space-Based and Ground-Based Laser Weapons,” Occasional Paper No. 5, Center for Strategy and Technology, Air War College (Maxwell AFB, AL: Air University Press, July 1998), 30. Estimates for laser transmission efficiency validated by Mr. Edward Duff of the Air Force Research Laboratory Directed Energy Directorate during discussions on 13 January 2010.

¹⁹ Duff, discussions with author.

²⁰ Nielsen, *Effects of Directed Energy Weapons*, 127.

²¹ Duff, discussions with author.

²² Possel, “Lasers and Missile Defense,” 28-30.

²³ Stephen G. Leonard, “Laser Options for National Missile Defense,” Air Command & Staff College, Maxwell AFB, AL: Air University Press, April 1998, 65-66. While amplification of the beam is not necessary, especially if the ground station generates the 4 to 10 megawatts posited by AFRL, amplification is possible.

²⁴ David M. Mason, “Directed Energy Weapon System for Ballistic Missile Defense,” Air War College, Maxwell AFB, AL: Air University Press, February 2009, 31.

²⁵ Air Force Research Laboratory, “Relay Mirror Technology,” U.S. Air Force Fact Sheet, Kirtland Air Force Base, NM, April 2006, <http://www.kirtland.af.mil/shared/media/document/AFD-070404-044.pdf> (accessed 31 October 2009). Also gained insight during Air War College student tour of Air Force Research Laboratory facilities at Kirtland AFB, NM from 24-28 Aug 2009.

²⁶ Duff, “4A – Globally Deliver Directed Energy and Non-Kinetic Effects,” Air Force Research Laboratory Directed Energy Directorate briefing on long-term research areas, August 2008. Also gained insight during briefings given to Air War College students during tours of Air Force Research Laboratory briefings, Kirtland AFB, NM, 24-28 Aug 2009.

²⁷ Ibid.

²⁸ Ibid.

²⁹ Ibid.

³⁰ Anderberg and Wolbarsht, *Laser Weapons*, 115.

³¹ Rolfsen, “Test of Laser from C-130H.” Test results also presented at the Directed Energy Professional Society Annual Convention, San Antonio, TX, November 2009.

³² Anderberg and Wolbarsht, *Laser Weapons*, 141-42.

³³ Matthew Mowthorpe, *The Militarization and Weaponization of Space* (Lanham, MD: Lexington Books, 2004), 121-25.

³⁴ “Russians Alter MiG-31 for ASAT Carrier Role,” *Aviation Week & Space Technology*, 17 August 1992, 63. In Matthew Mowthorpe, *The Militarization and Weaponization of Space*, 134-35.

³⁵ Mowthorpe, *The Militarization and Weaponization of Space*, 134-35.

³⁶ Lambakis, *On the Edge of Earth*, 124.

³⁷ Marc Kaufman and Dafna Linzer, “China Criticized for Anti-Satellite Test,” *The Washington Post*, 19 January 2007, A1.

³⁸ Lambakis, *On the Edge of Earth*, 124-25.

³⁹ Protocol IV of the United Nations Convention on Conventional Weapons (adopted on 13 October 1995) “prohibits the use and transfer of laser weapons designed to cause permanent blindness to unenhanced vision.” However, it does not address blinding as a form of collateral damage. It also does not prevent the development, storage, or disclosure of blinding laser weapons, nor are there any sanctions specified for violation of this protocol. (Source: Federation of American Scientists, <http://www.fas.org/nuke/control/ccw/> [accessed 8 Feb 2010]).

⁴⁰ Bob Preston et al, *Space Weapons: Earth Wars* (Santa Monica, CA: RAND, 2002), 20-21.

⁴¹ O’Hanlon, *Neither Star Wars nor Sanctuary*, 15.

⁴² T.V Paul, Patrick M. Morgan, and James J. Wirtz, *Complex Deterrence: Strategy in the Global Age* (Chicago: University of Chicago Press, 2009), 2-3.

⁴³ Emanuel Adler, “Complex Deterrence in the Asymmetric-Warfare Era.” In Paul, Morgan, and Wirtz, *Complex Deterrence*, 88-89.

⁴⁴ Air Force Doctrine Document 2-12, *Nuclear Operations*, 24 April 2009. In Air War College, Department of Joint Military Operations, *Warfighting I*, August 2009, 380.

⁴⁵ Joint Publication 3-14, *Space Operations*, 6 January 2009. In Air War College, Department of Joint Military Operations, *Warfighting I*, August 2009, 325-26.

⁴⁶ Mowthorpe, *The Militarization and Weaponization of Space*, 122-23.

⁴⁷ Jeff Hecht, “Optical System Can Help Stop Missiles,” *Laser Focus World*, Vol. 40, Issue 5, May 2004.

⁴⁸ Anderberg and Wolbarsht, *Laser Weapons*, 185-86.

⁴⁹ Ibid, 195.

⁵⁰ Ibid, 122-23.

⁵¹ Ibid, 151.

⁵² O’Hanlon, *Neither Star Wars nor Sanctuary*, 128-29.

⁵³ Ibid, 128-29.

⁵⁴ Department of Defense, “Plan for Operationally Responsive Space.” In Air War College, Department of Joint Military Operations, *Warfighting I*, August 2009, 367-69.

⁵⁵ Jonathan W. Campbell and Charles R. Taylor, “Power Beaming for Orbital Debris Removal,” and Peter Hammerling and John L. Remo, “Ablation Scaling Laws for Laser Space Debris Clearing,” Proceedings of Society of Photo-Optical Instrumentation Engineers Conference on High-Power Laser Ablation, Vol. 3343, Santa Fe, NM, April 1998.

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