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HOW IS U.S. SPACE POWER JEOPARDIZED BY AN ADVERSARY'S EXPLOITATION, TECHNOLOGICAL DEVELOPMENTS, EMPLOYMENT AND ENGAGEMENT OF LASER ANTISATELLITE WEAPONS?

by

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Contents

Page

Illustrations

Tables

Page

Preface

This paper analyzes how US space power is jeopardized if and when adversaries develop laser antisatellite weapons capable of attacking US military and commercial satellites. My motivation for the study was twofold: (1) to briefly educate political and military decisionmakers about lasers with their attractive and exploitable weapon characteristics for use against satellites, especially by adversaries of the US and (2) to describe some of the issues affecting changes in US military advantage in space given an adversary with advanced laser technology and the will and capability to attack US space assets.

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This paper should be of use and interest to persons concerned with US military doctrine, strategy, policy and force planning, as well as those interested in threats laser antisatellite weapons pose to US space assets.

Acknowledgment

The motivation, inspiration and drive to complete this project directly come from my love, devotion and commitment to my family; especially my wife, Nancy, and my two sons: Bennett and Austin. I sincerely thank and dedicate this project to Nancy, Bennett, Austin and the rest of my family for their support, understanding and encouragement during the course of this investigation.

Abstract

This research project discusses how an adversary's exploitation, technological developments, employment and engagement of laser antisatellite (ASAT) weapons may negatively impact the US ability to use space power to enhance terrestrial warfighting capability. After describing some exploitable, attractive laser weapon characteristics, the paper explains some laser lethality factors relating several key laser weapon parameters, such as range, pointing jitter, atmospheric attenuation, dwell time and target coupling. How ground-, air- and space-based lasers can theoretically be employed against space assets to inflict "soft" and "hard" satellite kills is also briefly discussed. Next, applicable US treaties and political considerations about laser ASAT weapons are presented. Finally, unclassified sources are used to assess the current level of laser ASAT weapons threat to US space assets and propose how an adversaries' laser ASAT weapons can jeopardize US space power's ability to enhance terrestrial warfighting.

Part 1

Introduction

This research project discusses how an adversary's exploitation, technological developments, employment and engagement of laser antisatellite (ASAT) weapons may negatively impact the US ability to use space power to enhance terrestrial warfighting capabilities. After describing exploitable, attractive laser weapon characteristics useful for ASAT weapons, Part 2 continues by explaining several laser weapon lethality factors. The laser lethality factors relate the significance of several central laser weapon parameters, such as range, pointing jitter, atmospheric attenuation, dwell time and target coupling. Several enabling laser technological developments are also presented to show why lasers have a future as ASAT weapons. Part 3 then briefly examines how adversaries can theoretically employ ground-, air- and space-based lasers against US space assets to inflict "soft" and "hard" satellite kills. Next, applicable US treaties and political considerations about laser ASAT weapons are presented. Part 4 then uses unclassified sources to assess the current level of laser weapons threat to US space assets and how an adversary may engage laser ASAT weapons against the US. Finally, Part 5 concludes the paper with remarks about how adversaries' laser antisatellite weapons can jeopardize US space power's ability to enhance terrestrial warfighting.

Part 2

Laser Antisatellite Weapons

Whereas those who have the capability to control the air, control the land and sea beneath it, so in the future it is likely that those who have the capability to control space will likewise control the earth's surface.

— General Thomas D. White, USAF, 1957[1]

Attractive Laser Weapon Characteristics

The laser is an excellent ASAT weapon candidate for adversaries to use against space assets. Appendix A gives an in-depth explanation and comparison of why lasers are the most likely ASAT weapons of choice when compared to several other types of directed energy weapon systems. In addition, Appendix B briefly defines and describes a laser and its basic operations. However, for our purposes, after introducing the exploitable, attractive ASAT weapon characteristics of a laser system, this chapter will focus on key laser lethality factors and advanced enabling laser technology developments.

Let's first consider the laser's ASAT weapons advantages of directionality, wavelength, modulation, output and speed of delivery.

Coherence and Directionality

Lasers have the key property that their output beam is coherent (extremely consistent) and highly directional. The high coherence of the laser is a manifestation of the regularity—the great predictability in time and space—of the light waves the laser produces. As for directionality, typical laser beams have beam divergences of less than a milliradian.[2] For example, a laser system with a one-meter output beam diameter and a 0.05 milliradian beam divergence would only expand to 25 meters after traveling 500 kilometers (311 miles). Thus, the laser's advantage as a satellite weapon is that coherence and directionality allows the highly accurate placement of energy on distant targets. Additionally, the beam, whether or not emitting in the visible range of the electromagnetic (EM) spectrum, is difficult to see or detect unless in the line of sight of the beam. The disadvantage is that accurately pointing the beam requires a high degree of control and precision.

Wavelength, Bandwidth and Tunability

Since today's lasers operate from the ultraviolet to the infrared regions of the EM spectrum, they offer great adaptability for various applications. Lasers are typically described by their wavelength (λ) in microns (μm or 10^{-6} meters) or nanometers (nm or 10^{-9} meters). Many lasers produce light of a very narrow band, called bandwidth, around a single, central wavelength that appears as a single, very pure color. For example, the neodymium yttrium aluminum garnet (Nd:YAG) laser, often used as a laser target designator, has a 1064 nm output beam with typical bandwidth of 0.45 nm.[3] Some lasers simultaneously operate and emit light on several different wavelengths, such as argon lasers that can emit light at 488 and 514 nm.[4] Depending on the application, multi-wavelength discrete emissions may or may not be beneficial to get maximum laser power on target.

Laser tunability, the ability to tune some lasers to flexibly operate over a range of wavelengths, adds great versatility and agility to laser weapons. For example, the tunable solid state titanium sapphire (Ti:S) laser has a tunable wavelength range from 660 to 1180 nm.[5] Since laser lethality is strongly wavelength dependent, tunability gives adversaries a great laser weapon advantage in that it is more difficult for the US to employ countermeasures to negate an adversary's laser ASAT weapons operating over a range of wavelengths rather than at discrete values.

Temporal (Time) Modulation

Laser systems can be designed to operate either continuously (called "continuous wave" or CW) or pulsed. By convention, a laser is usually called CW if the output beam lasts more than 0.25 seconds.[6] A pulsed laser is usually characterized by the time of its pulse duration. If a laser is pulsed repeatedly, the pulse repetition frequency (called *prf* and measured in Hertz) is the period from the beginning of one pulse to the beginning of the next pulse.[7] The duty cycle of the laser expresses the percent of the time the laser is emitting and is defined as the product of the pulse duration and prf. For example, a laser with a 25 percent duty cycle means the laser is emitting its beam a quarter of the time it operates. Most military operations use lasers operating CW or with very short, nanosecond pulses. For instance, the Air Force's Airborne Laser is a CW laser capable of 20 laser "shots" before needing laser fuel resupply, while laser target designators typically emit pulses of 10 nanoseconds in duration and 10 Hertz prfs.[8] By carrying their own laser fuel supplies, CW or pulsed lasers can "shoot" many times giving them the advantage of a "deep magazine."[9]

Output Power and Energy

As discussed in Appendix B, the laser beam contains energy in the form of electromagnetic radiation delivered by photons. Lasers operating with CW output are usually characterized by the *power* of the beam measured in Watts (W), while pulsed laser output is characterized by the *energy* in each pulse measured in Joules (J).[10] In addition, pulsed laser output is often characterized by average power for comparison purposes to CW lasers. The output power from CW lasers range from milliwatts (mW) to megawatts (MW). For example, the Mid-Infrared Advance Chemical Laser (MIRACL) is a US megawatt-class, CW, deuterium-fluoride (DF) chemical laser and is routinely used for static and dynamic target vulnerability studies.[11] The ability to adjust the power or energy output of a laser system on a target is also an advantage of using lasers to attack satellites due to increased flexibility and versatility.

All of the output power or energy of a laser is concentrated in a small solid angle (area/radius^2) due to the narrow beam. A high-power, or weapons-class, laser is a system that attempts to inflict damage on a target or aerospace vehicle by placing a large amount of energy on a small area. The result is a thermal kill, such as weakening and eventual rupture of structural components, ignition or combustion of flammable materials or destruction of thermally sensitive items in critical components.[12]

Weapons-class lasers operating CW are often preferred over pulsed lasers for military applications, such as laser ASAT weapons, due to the phenomenon known as laser supported combustion (LSC) that occurs when high-powered laser beams strike a target surface.[13] As the high-power laser vaporizes surface material from the target, the hot gas can absorb more laser energy. If enough energy is directed onto a target on a short time scale, the hot gas is rapidly ionized, producing a hot, dense plasma. The plasma then absorbs the incident light and virtually shields the target from the beam. LSC is a disadvantage for high-power pulsed lasers and the upper limit for putting laser energy on a target. If incident beam powers above the LSC point are used, then the effect of the laser is further degraded as the LSC develops into a detonation wave and travels up the laser beam to further decouple, or disengage, the laser from the target.[14]

Speed of Light Delivery

Since all laser beams are electromagnetic radiation, they travel at the speed of light, 3.0×10^8 m/sec. To help put this speed in perspective, light travels about one foot in one nanosecond. Therefore a "laser could attack an object 1,000 kilometers [622 miles] away in 3 thousandths of a second, while a high-speed rifle-bullet, for example, would have to be shot 16 minutes before impact with such a distant target."[15] Since lasers can attack targets at the speed of light, laser beams can engage a single target and then move on to engage other targets almost instantaneously, even if targets are relatively far away. If the target can be detected and tracked visually, then the laser beam can be placed on target and, if sufficient energy is delivered, the desired damage effect can be achieved. This key characteristic is very useful during operations where time is critical and the engagement range of the target, such as a satellite, is very long.

Key Laser Weapon Lethality Factors

In general, the lethality, or damage capability, of a laser weapon depends on the laser system, how the beam propagates from the laser to the target and how the beam interacts or delivers energy onto the target, such as a satellite. The laser weapon system should provide a laser beam, like a light saber, of highest beam quality and maximum power, but the way the beam gets to and then interacts with the target is important and limits a laser's effectiveness to inflict damage.

As the laser beam propagates through the atmosphere, several linear effects, such as diffraction, absorption, beam jitter, scattering and atmospheric turbulence, as well as the non-linear thermal blooming effect, can degrade the laser's effectiveness.[16] First, as for linear effects, diffraction is a natural phenomenon that causes the beam to diverge or bend as the beam transmits through focusing and steering optics. To ensure maximum power on target and high beam quality, the aim is to minimize beam losses (strehl) and diffraction effects.[17] Since the beam's area or "spot size" is fundamentally limited by diffraction, to obtain the smallest spot size possible, in principle, one should use the shortest wavelength and largest diameter optics available to approach the diffraction-limited spot diameter (proportional to the beam wavelength and inversely proportional to the beam's optics effective diameter). Second, absorption, or atmospheric attenuation, of the laser beam by water and air occurs in the atmosphere as discussed above. Third, by beam jitter we refer to beam spreading, often caused by mechanical vibrations, track scintillation, track sensor noise and aimpoint jitter, that ultimately affect the beam's power on target.[18] Fourth, the laser beam is scattered, or redirected, by particles in the atmosphere, principally the result of raindrops.[19] However, hail, snow, clouds, smoke and dust can also scatter a laser beam. The final linear effect, atmospheric turbulence, causes the laser beam to spread as the atmosphere changes along the path of propagation. Atmospheric turbulence depends heavily on the range to the target and only weakly on the wavelength of the laser beam. The longer the range to the target, the greater the laser beam is spread, and thus reducing concentrated power on target due to atmospheric turbulence.[20] As for the non-linear thermal blooming effect, atmospheric changes in the wind velocity, temperature, and density of air combine to cause localized beam focusing and heating in the atmosphere.[21]

All the above mentioned effects rob the laser beam of valuable power and "punch" on the intended target, if the laser beam must travel through the atmosphere. However, when the laser beam travels through less atmosphere, such as when employed on an air-based platform above the clouds, then the negative atmospheric effects are reduced for air-to-space engagements. To inflict the maximum laser weapon damage, the employment of a space-based laser would eliminate all atmospheric effects and maximize power on a satellite target in a space-to-space force application.

Once the laser beam arrives on the target, such as a satellite, there are several factors that determine the induced damage effects. Depending upon the wavelength of the incident laser beam and the material, the light is transmitted, absorbed or reflected by the solid materials. All lasers deposit or "couple" their energy on the target surface, and if the target is a metal, the metal may reflect more than 90 percent and absorb less than 10 percent of the incident laser energy.[22] For example, consider a fictitious 2 megawatt carbon dioxide (CO_2) laser attack directed against a US satellite orbiting at 60 miles and affected by various propagation factors as shown in Figure 1. The aluminum parts of the US satellite targeted by a ground-based CO_2 laser ($\lambda = 10.6\ \mu m$) would reflect 98, transmit 0, and only absorb 2 percent of the incident laser energy.[23] At the surface, thermal conduction carries the deposited energy into the interior of the target where the target begins to heat, melt or vaporize. Other factors, such as surface coating (paint or antireflective coatings), degree of polish and thickness, strongly affect laser coupling to targets. In addition to coupling as much energy onto a small area or spot of the target surface as possible, the amount of time the laser beam is directed onto the surface (dwell time) and whether the laser is CW or pulsed all combine to determine the induced damage.[24] For example, a good damage criterion rule of thumb for effective laser lethality is to deposit 10,000 Joules per second (10,000 Watts) of laser energy within 1 cm^3 of the target.[25] This will vaporize 1 $gram/cm^3$ of most materials so fast that thermal conduction and diffusion can't significantly dissipate the deposited laser energy.

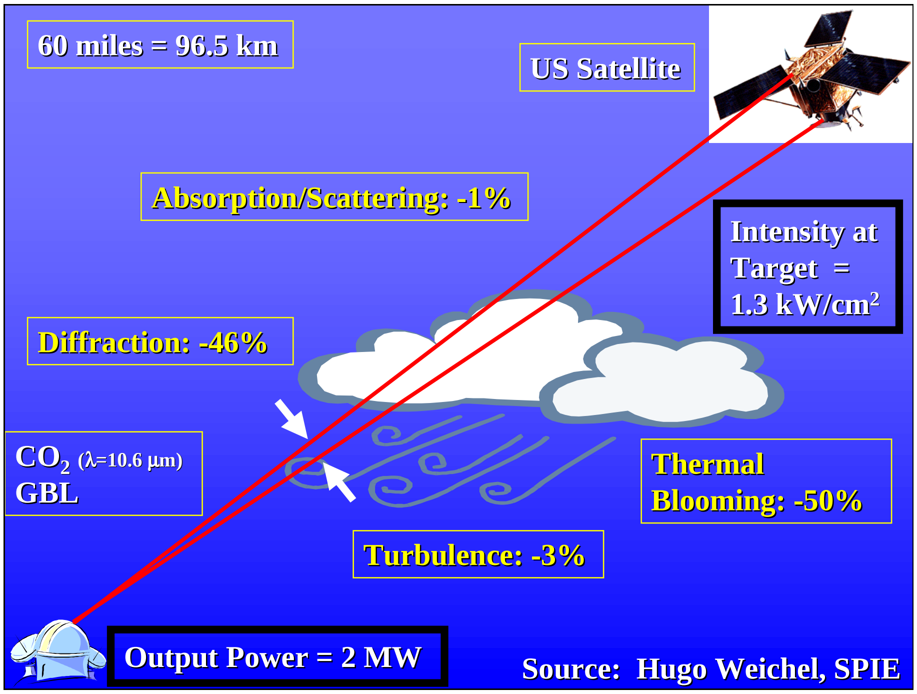

Figure 1. Hypothetical CO_2 GBL ASAT engagement.

Laser Technological Developments

Several emerging laser technologies may make laser ASAT weapons attractive to adversaries of the US in the near future. Major engineering advances in the form of improved laser materials, new wavelengths, high efficiencies, thermal management, optical materials and components, sensors and computer processors are maturing rapidly.[26] In addition, laser technology developments in building compact, medium to high-power, short wavelength lasers with high beam quality are coming of age.

Technological innovations exist that reduce the size and weight penalties driven by the laser beam spot on satellite targets and support laser weapon designs optimized for laser ASAT mission requirements. These innovations are in the form of adaptive optics, phase conjugation, diode pumping of lasers, thin membrane optics and proven high-power laser systems.[27] Adaptive optics and phase conjugation are two demonstrated technologies capable of producing near perfect beams in the presence of major optical distortions, like atmospheric propagation effects.[28] Adaptive optics systems use lasers and computers to determine various path distortions, then computers manage deformable optics, or mirrors, whose face can be altered hundreds of times per second to help compensate for atmospheric distortions.[29] In addition, the Russians pioneered and the US have successfully demonstrated stimulated Brillouin scattering (SBS) phase conjugation methods to correct wavefronts and improve the beam quality of laser beams.[30] Adaptive optics and phase conjugation can also remove the effects of path turbulence and permit the use of lightweight, low cost, imperfectly configured optical components. Additionally, adaptive optics and phase conjugation have been used to correct for distortions in the lasers, distortions that otherwise build rapidly to degrade laser performance as the lasers are operated at higher power levels. Next, diode pumping of lasers, where laser diodes pump or drive solid state lasers like Nd:YAG, are more efficient than traditional flashlamp pumping methods while reducing the internal heating of the laser material. This improves laser reliability and extends life expectancy. Technical advances in diode pumping have led to the development of compact, multi-kilowatt average power solid state lasers.[31] In addition, thin membrane optics (inflated structures where electrostatic forces shape the membrane) offer the potential of fabricating large, lightweight optics. Most likely, thin membrane technology would be applicable as a space-based system to minimize gravitational distortion and aerodynamic forces. Finally, new laser wavelengths and pulse formats are now available, such as diode pumped solid state lasers, with short wavelength and repetitive long pulse format, and chemical oxygen iodine lasers (COIL) with short wavelengths.[32] For example, the US has proven high-power lasers are feasible by demonstrating and operating the multi-megawatt MIRACL at the High Energy Test Facility, the multi-megawatt COIL built for use on the Airborne Laser and the Tactical High-Energy Laser (THEL) developed in a US joint effort with Israel for mobile ground-based air defense.[33]

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Part 3

Laser Antisatellite Weapons Employment and Engagement

In the emerging, less controllable world of global commerce and borderless nations, the military medium of dominance and, hence, of choice to power elites will be the aerospace continuum because of its universal, rapid access and unique vantage point. Hence, the control and exploitation of that medium, more than any other, will offer the widest range of military options and the greatest degree of military power.

— Carl H. Builder, 1994[1]

Laser ASAT weapons may soon be employed by hostile nations to engage and jeopardize U.S space assets. By employment we mean positioning the weapon system within striking range of its target so it is ready to engage.[2] And engagement means the actual process of detecting, acquiring, tracking and directly attacking satellites. Let's consider three basing schemes for potential laser ASAT weapon systems: ground-, air- and space-based, where we'll very briefly analyze the required laser system, the propagation medium and the possible satellite targets. Tables 1 and 2 provide a concise summary and comparison of the three basing-scheme results. After describing these possible laser weapon-basing schemes, we'll discuss "soft" and "hard" satellite kills and various US treaty and political considerations.

Ground-based Laser Systems

Ground-based, or in general earth-surface-based, lasers (GBLs) used alone or with a space-based relay mirror architecture (where the laser beam is bounced off relay mirror satellites) could be used as ASAT weapons. Water-based platforms, such as ships, could also serve as a stable platform for the laser to fire, but we'll focus our discussion on GBLs deployed on land. The GBL required to project a high-power laser beam to attack orbiting satellites would need a powerful laser, large telescope(s), atmospheric compensation, high accuracy pointing and tracking systems, and imaging or surveillance capability for satellite damage assessment.[3] The fire control process would be to acquire (detect) the satellite target, establish a track on or position of the satellite, flood the target with low power photons for imaging, stabilizing the target image within a fine track camera's field of view, and establishing the laser aimpoint on the satellite for attack.[4] Because a GBL is on the ground, there's virtually no physical size limitation and local power utility grids can supply power requirements while other energy and laser fuel resources are readily available. In addition, while the high-power laser systems are complicated, system reliability is high since people can access, maintain and easily upgrade the GBL system.

To strike a satellite target from the ground, the GBL would need to overcome the various atmospheric propagation phenomena as discussed earlier. Therefore the wavelength of the laser ASAT weapon must be carefully chosen to easily pass through the atmosphere. Based on CW power and atmospheric transmission capabilities, the most likely CW laser candidates would be the COIL, the DF or the hydrogen-fluoride (HF) overtone laser since they have good atmospheric transmission characteristics (95%+) while operating at 1.315, 1.35 and 3.5-4.0 microns, respectively.[5] Also, in addition to CO_2 lasers, high average power Nd:YAG systems operating at 1.064 microns might work as effective GBLs. Pulsed Nd:YAG weapons-class lasers may also serve as GBLs, but as mentioned earlier, LSC is a disadvantage that sets the upper limit for putting pulsed laser energy onto a satellite target. Besides transmission wavelengths, GBLs are greatly affected by weather. Therefore, placing the laser system at a location with exceptionally clear weather most of the year would be best so satellites could be attacked when within the laser's field of view or by using a space-based mirror relay architecture.

Satellite targets in jeopardy of being damaged by GBLs depend upon the GBL's location and on the orbit of the satellite. For instance, one option for an adversary to employ GBLs, especially during a conflict, would be to effectively exploit a unique ground location geometry characteristic. Namely, all satellites, regardless of their launch point or inclination, pass through their antipodal point (the point directly opposite the launch site, 180 degrees around the earth) during their first orbit.[6] The majority of more than 700 US military and civilian satellites are in one of three orbital altitude regions above the surface of the earth; specifically, low earth orbit (LEO=60-300 miles), medium earth orbit (MEO=300-22,300 miles) and geosynchronous (synchronized with the earth's rotation) earth orbit (GEO=22,300 miles).[7] Due to range limitations, adversary GBLs would be most lethal to the closest current LEO and MEO orbiting satellites; for instance, the Defense Meteorological Satellite Program or DMSP (weather data collection), the Global Positioning System or GPS (worldwide navigation), Globalstar (communications), Iridium (mobile communications), Landsat (remote sensing) and the Satellite Pour l'Observation de la Terre or SPOT (remote sensing).[8] However, since these satellites orbit in various orbital planes and travel at different velocities, they would give an adversary complicated engagement challenges. On the other hand, satellites in GEO, such as the Geostationary Operational Environmental Satellite (storm monitoring and tracking) or Loral Orion (communications), have long ranges, but are easy to engage due to their earth synchronized orbit. Satellites in GEO are GBL engageable, but require very high-power lasers of exceptional quality. The effectiveness of GBLs are also limited to satellite view angles. GBLs are most lethal when the satellites are directly overhead or perpendicular to the GBL's position on earth. To counter this disadvantage, space-based mirror relays can enhance a GBL's ASAT effectiveness. However, significant increases in relay mirror system costs, ASAT system complexity and ranges pose serious operational considerations for using a space-based relay mirror satellite architecture to conduct ASAT missions.

Air-based Laser Systems

Air-based, or airborne platform-based, lasers (ABLs) used alone or with a space-based relay mirror satellite architecture could also serve as an ASAT weapon. A wide-body aircraft could serve as the highly mobile airborne platform and operate above the clouds to minimize weather effects. The ABL required to project a high-power laser beam to attack orbiting satellites would still need a megawatt-class laser, transfer and adaptive optics, substantial atmospheric compensation, high accuracy pointing and tracking systems, and imaging or surveillance capability for satellite damage assessment.[9] The acquisition, tracking, pointing and fire control processes would mirror image the GBLs process and involve acquiring the target, tracking the target and handing it over to higher levels of precision, selecting an aim point, pointing the laser at the aimpoint, perform mode and beam control for the system and assess inflicted damage effects.[10] Since the ABL would operate in the air, there are moderate size, weight, prime power (laser energy source), reliability, maintenance and adequate laser fuel supply limitations. In addition, since the high-power laser systems are complicated, system reliability is moderate since people can access, maintain and upgrade the ABL system's computer software and equipment hardware in hours to days to weeks, depending on the situation.

To strike a satellite target in space from the air, the ABL would also need to overcome transmission limitations, turbulence and some thermal blooming to propagate the laser beam through the atmosphere. As before, the adversary would need to carefully choose lasers with wavelengths able to pass through the atmosphere. Based on CW multi-megawatt power, compactness and atmospheric transmission capabilities, the most likely CW laser candidate would be a COIL since this laser exhibits good atmospheric transmission characteristics (95%+) while operating at 1.315 μm.[11] Also, high average power Nd:YAG systems operating at 1.064 microns might work satisfactorily, although they're not as powerful as the COIL. Due to the airborne platform moving through air, atmospheric turbulence would increase significantly over GBLs and cause the laser beam to bend even more. Since the ABL would principally operate above the clouds, atmospheric blooming due to water droplets in the air would have a negligible effect on beam divergence. Primarily due to drastic increases in turbulence effects, the atmosphere can substantially reduce laser power on target and must again be accounted for using atmospheric compensation. Therefore, the ABL system would be best deployed within a few hundred kilometers of the target satellites due to range and power limitations.

Satellite targets in jeopardy of being damaged by ABLs again depend upon the ABL's location and on the orbit of the satellite. For instance, ABLs, especially during a conflict, would have the flexibility and versatility to fly to target ranges within hours of a conflict and have the advantage of persistence to remain in close proximity. Due to range limitations, an adversary's

ABL would also be most lethal to the closest current orbiting LEO and MEO US satellites; for instance, DMSP, Iridium, or Landsat.[12] However, since these satellites orbit in various orbital planes and travel at different velocities, they would still give an adversary complicated engagement challenges. On the other hand, satellites in GEO are at such high altitudes that they're essentially out of the effective range of a COIL-based ABL.

Space-based Laser Systems

Space-based lasers (SBLs) used alone or with a space-based relay mirror satellite architecture could also be used as an ASAT weapon. An adversary's SBL, just as with the GBL, could attack orbiting satellites, but would still need a powerful laser, a large telescope(s), high accuracy pointing and tracking systems, and imaging or surveillance capability for satellite damage assessment.[13] The SBL fire control process would be to acquire (detect) the satellite target, establish a track on or position of the satellite, flood the target with low power visible light for imaging, stabilizing the target image within a fine track camera's field of view, and establishing the laser aimpoint on the satellite for attack.[14] This fire control scheme is similar to those explained before; however, cheaper laser illuminators and imaging cameras could be used since the beam wavelength for space-to-space propagation is not an issue. Because an adversary would most likely deploy a SBL on a MEO platform due to space lift capabilities, there are substantial size, weight, prime power, reliability, maintenance and adequate fuel supply limitations, even more than with the ABL. In addition, since the high-power laser systems are very complicated, SBL system reliability is low since people cannot access, maintain or upgrade a SBL system for up to months or years at a time.

To strike a satellite target in space-to-space engagements, the SBL would not need to overcome the transmission, turbulence and blooming atmospheric limitations inherent with the GBL and ABL as the laser beam propagated. Based on CW power requirements, the most likely CW laser candidate for a SBL would be the HF laser capable of producing multi-megawatt power at 2.7 μm wavelength with practically 100% transmission in space.[15] Therefore, the laser system would be best placed at a location so it could attack satellites when in line-of-sight range or by using a space-based mirror relay satellite architecture.

Satellite targets in jeopardy of being engaged by SBLs are driven by the SBL's location and on the orbit of the satellite. An adversary using a few orbiting SBLs or an SBL and a space-based mirror relay constellation could essentially place all US space assets at great risk of engagement and exert global space control dominance. Due to range limitations, SBLs would be most lethal to the closest LEO and MEO orbiting satellites; for instance, the DMSP, GPS, Globalstar, Iridium, Landsat and SPOT.[16] However, as before, since the SBLs and target satellites orbit in various orbital planes and travel at different velocities, they would still give an adversary complicated engagement challenges. On the other hand, satellite targets in GEO would have shorter ranges to the SBL than the GBL or ABL and would be much easier to engage.

Table 1. Summary and Comparison of Ground-, Air- and Space-Based Laser ASAT Weapon Scheme Mission Effectiveness Impacts

ASAT Basing Scheme	Laser System		Impacts on ASAT Mission Effectiveness					
	Type	Modulation	Laser Beam Atmospheric Propagation	Laser System Physical Size	Laser System Power Source	Laser Fuel Supply-Resupply	Laser System Reliability	Laser System Accessibility
GBL	CO_2 COIL DF HF Overtone Nd:YAG	CW/Pulsed CW CW CW CW/Pulsed	High	Low	Low	Low	Low	Low
ABL	COIL Nd:YAG	CW CW/Pulsed	Medium	Medium	Medium	Medium	Medium	Medium
SBL	HF	CW	Low	High	High	High	High	High

Table 2. Summary and Comparison of Ground-, Air- and Space-Based Laser ASAT Weapon Scheme Impact or Risk to Satellite Targets

ASAT Basing Scheme	Laser System		Impact or Risk to Satellite Targets					
			No Relay Mirrors			Single Relay Mirror		
	Type	Modulation	LEO	MEO	GEO	LEO	MEO	GEO
GBL	CO_2 COIL DF HF Overtone Nd:YAG	CW/Pulsed CW CW CW CW/Pulsed	Medium	Medium	Low	High	High	Medium
ABL	COIL Nd:YAG	CW CW/Pulsed	High	Medium	Low	Medium	Medium	Low
SBL	HF	CW	High	High	Medium	High	High	High

Laser Weapons used for Satellite "Soft Kills'

Laser weapons offer a subtle means of satellite engagement—disrupting, disabling, degrading, confusing, deceiving, delaying, denying or destroying—and may be performed, overtly or covertly, by adversaries for strategic attack. We'll classify laser ASAT attacks without the means to verify an immediately or totally destroyed satellite as a "soft kill." In general, lasers inflict damage on targets; i.e., satellites, by directing laser energy onto the target area for a certain time period. CW lasers need to dwell on the target surface for a sufficient amount of time to inflict thermal induced damage, while a pulsed laser's "kill mechanism" is to damage targets by blowing off part of the surface, thus forming a plasma.[17] Potential enemies can attack US space-based systems by attacking some or all of their major subsystems: attitude control; electrical power and distributions; thermal control; structural; tracking, telemetry and control; and other payload subsystems.[18] Many US military and commercial satellites are particularly susceptible to laser attack.[19] For example, if an adversary used a laser to engage the electrical and power distribution system of a satellite, possibly the solar panels, the effect might be to damage the solar panels. Even with batteries as power backup, the result of attacking the solar panels would probably degrade the effectiveness and usable lifetime of the targeted satellite. Due to the long length of time for such an attack to negatively affect the satellite mission or purpose, this example would constitute a soft kill. The negative effect may or may not be verifiable until long after the attacks have concluded. For instance, if the satellite were covertly and regularly attacked at low laser powers for brief periods of time, perhaps upon every pass overhead when in range, the attacks might go undetected and appear as natural satellite lifetime degradations. Satellites are not typically designed to quickly redistribute laser-induced heat throughout all its parts; therefore, laser attacks might proceed at a leisurely pace. A typical laser ASAT attack may have a 100 second engagement time, equivalent to the satellite exposure time of a low earth orbit satellite to a GBL or ABL.[20] Since energy, area and time all enter into satellite damage thresholds, the threshold is usually expressed in terms of beam intensity equal to power/area and measured in Watts/cm^2. For a successful "soft kill" attack, intensities of ten Watts/cm^2 delivered on target are adequately lethal to many satellites.[21]

Laser Weapons used for Satellite "Hard Kills"

Laser weapons also offer unmistakable means of strategic attack against satellites that may be performed, either overtly or covertly, by adversaries that we'll classify as "hard kills." A hard kill for a satellite would mean the ability to <u>verify</u> an immediate and catastrophic destruction of a targeted satellite rendering it unable to operate. As mentioned earlier, potential enemies can attack US space-based systems by attacking some or all of their major subsystems: attitude control; electrical power and distributions; thermal control; structural; tracking, telemetry and control; and other payload subsystems.[22] The difference between a soft and hard kill is the time to inflict damage that's a function of laser beam energy, beam area and time the laser beam is on target. To immediately destroy almost anything, we need to properly apply 10,000 Joules of energy based on two assumptions: (1) to vaporize 1 gram of almost any material, such as aluminum, requires approximately 10,000 Joules of energy and (2) the removal of 1 gram of material from a vital spot on a target will most likely destroy the target.[23] Due to the inability of most lasers to "hit" a satellite with 10,000 Joules of energy, adversaries could still produce spectacular and prompt satellite destruction of some US satellites at about 1,000 Watts/cm^2 (1,000 Joules of energy applied for 1 second) when directed onto a satellite.[24] For example, an adversary could use a laser to destroy a US satellite by igniting or expending the satellite's fuel, by putting a hole through the skin and fuel tank of the satellite, by rupturing pressure vessels, by destroying solar panels, by blinding sensors, or by damaging antennas. This type of direct attack would inflict immediate, verifiable damage and possibly cause the satellite to tumble out of control or explode. The appropriate time on target to immediately destroy a satellite depends upon the laser system and target satellite's location, but should not need more than several seconds at intensities greater than 1,000 Watts/cm^2.

US Treaties and Political Considerations

Initial ASAT arms control treaty negotiations between the US and Russia began as far back as 1978; however, any negotiated ASAT treaty was viewed as unverifiable and inequitable by the US, just like the Anti-ballistic Missile Treaty (ABMT), and hence would not be in the national interest.[25] Several US treaties indirectly govern the use of lasers as ASAT weapons against satellites; such as the Outer Space Treaty (1967), the Direct Communications Link Agreements (1963, 1971, 1984), the International Telecommunication Convention and the Anti-ballistic Missile Treaty,[26] but the US does not have, nor is currently pursuing, an ASAT treaty.[27] The Outer Space Treaty is relevant but is not directly applicable to laser ASAT weapons because it prohibits weapons of mass destruction deployed in space, but not conventional weapons, such as lasers.[28] However, the Outer Space Treaty prohibits interfering with other states' space-related activities without prior consultation and, depending upon interpretation, may indirectly prohibit areas or self-defense zones where a laser may be potentially employed in space.[29] The Direct Communications Link Agreements and the International Telecommunication Convention are applicable since they prohibit nations from interfering with communications systems of other nations without prior consultation.[30] Therefore, if a laser ASAT attacked a US communications satellite, these agreements would apply.

The ABMT is indirectly relevant to laser weapons because any laser ASAT weapon could possibly serve the dual role as an anti-ballistic missile (ABM) weapon. For instance, one state could theoretically develop ABM technologies and components and remain legal by testing and deploying them against satellite; i.e., non-ABM, targets. A US political advantage is that if Russia used the GBL concept as their one ABM defense, the ABMT would stop Russia from placing any laser weapons in space. In addition, according to the Helsinki agreement, the US and Russia are prohibited from placing any ABM or theater ballistic missile defense (TMD) components, such as relay mirrors, in space.[31] However, the Helsinki agreement did not prohibit an ABL concept laser source, like COIL, for TMD since the ABL is based on other physical principles (OPP).[32] Specifically, the Second Agreement Statement reached at Helsinki prohibits the development, testing or deployment of space-based TMD or other non-ABM components based upon OPP, such as lasers capable of substituting for TMD interceptors. In addition, the development, testing or deployment of land-, sea- or air-based TMD or other non-ABM systems based on OPP is *not* constrained or prohibited by the Helsinki agreements.[33] But realize that a laser weapon not constrained or prohibited by either the First or Second Agreed Statements *could* be proscribed by the ABMT itself or subsequent agreed statements in the future, such as the agreed statement concerning OPP. This interpretation of the ABMT opens the ABL with relay mirror architecture up for further ABMT discussions and possible renegotiations. The SBL options available to Russia would add great complexities to any ABMT discussions since they would add an entirely new class of space-based weapons.

In sum, significant political issues are likely to arise with nations developing laser ASAT missions since an overt or perceived attack on US satellites (military and possibly commercial) would most likely be viewed as a military attack on the US and possibly an act of war.[34] However, would the US have sufficient political and national will to initiate a conflict if only a space system; i.e., a satellite, were damaged or destroyed without any loss of life? If not, then what actions would the US take?

Notes

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Part 4

Laser Antisatellite Weapon Threats

Space is an area of vital concern to the military strategist. It is a new medium of operations where the actions of our opponents must be closely observed by those of us concerned with national security. It is also a region where our own activities could enhance our security against earth-based and space-based threats.

— General Bernard A. Schriever, USAF, 1965

According to a recent RAND report, “no nation possesses an operational ASAT capability that poses a significant threat to US national security space systems;” however, many nations have GBLs able to send directed energy into space.[1] Since it’s unknown what damage GBLs could do to US satellites, especially those in LEO, current GBL systems may already afford adversaries a rudimentary laser ASAT capability. Let’s consider Russia, China and a few emerging threats based on a political will and laser capabilities perspective to assess the laser ASAT weapon threat to US space assets and national interests.

Russian Laser Threat Assessment

Russian National Security Concept—Political Will. According to Russia’s national security concept, although the Russian economy is the key element, the focus is to guarantee Russia's sovereignty and ensure the country remains a great power.[2] One of the threats to national security of the Russian Federation is that Russia is in danger of losing a leading role in scientific research.[3] On the international scene, the main threats are a reduced role for the United Nations, a weakened role for Russia, NATO enlargement, NATO operating beyond its members' borders, possible foreign bases near Russia, weapons proliferation, claims on Russian territory, poor Commonwealth of Independent States (CIS) integration, terrorism, information policy, ecological problems and transnational crime.[4] To guarantee Russian national security, the main tasks are to spot threats in good time, guarantee Russia's sovereignty and integrity, ensure the economy is socially oriented, reduce reliance on foreign technology and improve the balance of power between Moscow and the regions.[5] They also include the need to guarantee equal and mutually beneficial cooperation with the world's leading nations, and increase and maintain Russia's military potential. For foreign policy the priorities are to simplify the multilateral nature of relations particularly through the UN Security Council, develop relations with the CIS, defend citizens abroad, participate in international organizations, take part in peacekeeping, help control nuclear weapons and adapt existing treaties to new circumstances.[6] In the military sphere, Russia needs to be equipped to respond adequately to any threats that may emerge in the 21st century and their main aim is to deter aggression through a combined arms approach, including antispace operations.[7] Of course, Russia maintains the right to use all available means, including nuclear or laser weapons, to repel aggressors.

Russian Laser Capabilities. Even though Russia is concerned about the danger of losing a leading role in scientific research and currently lack active SBL or ABL programs, they have already demonstrated respectable GBL systems capable of a laser ASAT mission. For example, Russia pursued a SBL concept program, called “Skif,” until around 1990 when the program was apparently cancelled.[8] The Skif-DM module was a test-bed space-based laser system flown as part of the Polyus spacecraft in 1987, but failed to reach orbit.[9] Unclassified resources did not reveal any Russian ABL programs. On the other hand, Russian ground-based high-power laser research activities continue. For instance, in 1987 USAF General John Piotrowski said the former Sary Shagan laser facility near Lake Balkhash in Kazakstan was capable of killing US satellites below 400 kilometers (about 250 miles), damaging satellites up to 1,200 kilometers (about 750 miles) and damaging sensors and geosynchronous satellites at 35, 900 kilometers (about 22,300 miles).[10] In 1997 Russian President Boris Yeltsin wrote to US President Bill Clinton that at one time the Russians possessed an ASAT capability, but renounced it as soon as they realized the futility of a first-strike notion.[11] However, this letter probably serves to confirm that Russia still retains their ASAT capability.

Despite abandoning the Sary Shagan, the Russians may still be using other possible laser facilities, such as Nurek, Semipalatinsk and Troitsk.[12] Before leaving Sary Shagan, the facility operated ruby and pulsed CO_2 laser systems that may have been transferred to other facilities.[13] For instance, the former Soviet Union's defense weapons facilities at Nurek (about 25 miles southeast of Dushanbe in Tajikistan) and Semipalatinsk may still be in use and house the equipment formerly at Sary Shagan.[14] In addition, in 1989 a US Congressional delegation visited a 1 megawatt high-power gas laser at Troitsk near Moscow that reportedly was linked to former-Soviet laser ASAT efforts as early as 1980.[15] Finally, Russian Academician Fedor Bunkin, State Prize Laureate for work in laser weapons, believes a Russian pulsed chemical laser superweapon is possible in the next few decades, especially since a state-scientific-technical center has been directly working on the chemical laser problem for the last 30 years.[16]

Scenario One. Due to the ABM Treaty, nuclear deterrence and the low likelihood of a nuclear war between the US and Russia, let's consider a scenario involving a major conventional war between either the US and Russia or their allies. Both countries extensively use satellites to provide navigation, targeting, communications, surveillance and reconnaissance. The Russian military doctrine that stresses initiative and massive force and the Western increasing reliance on space systems that are vulnerable to attack would tempt Soviet "soft and hard kill" ASAT attacks on US and allied space systems—possibly preemptive. Simultaneous or near simultaneous laser ASAT attacks on US collection and communications satellites, particularly those in LEO, would significantly reduce information flow and negatively effect US awareness, understanding and control of the battlespace. Since the US military has migrated key intelligence, surveillance and reconnaissance, strategic and theater level warning, weapon's guidance, communications, command and control, and environmental monitoring functions to space, unprotected space-based warfighting assets are at risk to laser ASAT attacks.[17] Advanced weapons technology, such as smart GPS guided munitions, and critical reliance on space assets to enhance warfighting capabilities, such as Landsat for remote sensing, now makes the US vulnerable to attacks by potential adversaries if our access and use of space is denied or degraded. For instance, if any part of the GPS (ground or space systems) was attacked and damaged, civilians and the US military would endure degrades in worldwide-navigation, precise time transfer and nuclear detonation detection capabilities. Since smart GPS guided munitions rely exclusively on GPS to precisely place munitions on targets to maximize combat effectiveness and minimize collateral damage, any GPS degradations would significantly limit US leadership plans and options to deter and stop Russian aggression. Also, if the only existing Landsat were destroyed, then the imagery Landsat provides to the US military to map and plan tactical operations would be lost. Russians know that due to the tremendous military advantage of US space power, they cannot win a conventional or nuclear war, without first drastically degrading or destroying US satellite systems.

Thus, if the US did not quickly respond in kind, the Russian forces would have virtual unlimited use of space for force enhancement while negating US space assets and warfighting capability. US satellite attrition and vulnerability to hostile ASAT attacks, coupled with the US inability to replace satellites in a timely manner, would place US forces at a great disadvantage for possibly months to years. The knowledge of the value of space and satellite-delivered information would strengthen Russia’s motivation to conduct strategic ASAT attacks very early in any possible conflict.

Chinese Laser Threat Assessment

Chinese Security Strategy--Political Will. In July 1998, China issued a Defense White Paper that authoritatively outlined China's vision of a post-Cold War Asia security order.[18] China’s security views center around The Five Principles of Peaceful Coexistence: mutual respect for territorial integrity and sovereignty, mutual non-aggression, non-interference in each other's internal affairs, equality and mutual benefit and peaceful coexistence.[19] In the area of multilateralism, in a reversal of its position earlier in the decade, China espouses to settle disputes peacefully based on mutual trust and promote understanding through dialogue and cooperation.[20] Since security is "mutual" these dialogues should not be confrontational or aimed against another country or infringe upon the security interests of any other nation. China prefers a multilateral approach oriented toward discussion without commitment. It prescribes a non-binding approach where all participants have the opportunity to air views, but absent consensus, does not bind the participants to a specific course of action.[21] The US on the other hand, is frequently impatient and prefers a more issue-oriented problem-solving approach with China.

The most fundamental disagreement in concepts of security between the Chinese and US is the area of bilateral military alliances and regional stability. China is against military alliances.[22] China asserts US military alliances, sometimes characterized as Cold War relics, are US initiatives to reinvigorate and strengthen bilateral alliances and have added to international instability.[23] China may now see its security in global rather than regional terms. It also suggests that China is prepared to become more proactive in trying to shape the international environment and assert its security interests. Although China wants to reduce the international threat theory and be perceived as a responsible actor in Asia, recent theater missile defense initiatives challenge this view.[24] Since the US postures itself as the Asian regional stabilizing presence, it is no longer enough for China to simply be opposed to US regional "hegemonism." An alternative vision for the region is required as tangible evidence of China's ability to articulate a security system that would continue to provide peace and stability if the US approach is to be replaced.

More than 50 years ago China and the US embarked upon a competition of ideas and ideologies for the future of Asia. Those competing ideas resulted in war and instability for almost 25 years, but are less likely today.[25] In addition, the differing, or competing, visions of Asian security that the United States and China hold are not inherently destabilizing as long as China does not try to undermine the foundation of America's security posture in Asia and abroad.

Chinese Laser Capabilities. According to a Pentagon report, China's People's Liberation Army (PLA) is building lasers to destroy satellites--“hard kill”--and already has beam weapons capable of damaging sensors on space-based reconnaissance and intelligence systems--“soft kill.”[26] Consequently, China could degrade or blind US intelligence and military space equipment, systems vital for deploying US military forces in current and future warfare. In addition to military satellites, these laser ASAT weapons also could be used to disrupt, degrade or cripple commercial communications and navigation systems. The report, released by the House National Security Committee, indicated the PLA has obtained a variety of technologies "that could be used to develop an antisatellite weapon."[27] "China already may possess the capability to damage, under specific conditions, optical sensors on satellites that are very vulnerable to lasers," the report said. "Given China's current level of interest in laser technology, it is reasonable to assume that Beijing would develop a weapon that could destroy satellites in the future."[28] For example, China has developed and tested, possibly with the assistance of former Russian scientists, an advanced laser defense technology that can shoot down incoming missiles at low altitudes, a technology capable of being adapted to a laser ASAT mission.[29] Improved laser weapons capability is among several aspects of China's drive to develop high-technology weapons. Congress asked the Pentagon to assess China's strategy and military modernization efforts, including whether Beijing plans "to place weapons in space or to develop earth-based weapons capable of attacking space-based systems."[30] US intelligence officials believe the systems most vulnerable to laser attack are satellites operated by the National Reconnaissance Office, that take photographs from space, and the National Security Agency, that monitor communications.[31] The ability to damage or destroy satellites will provide China with a strategic attack weapon against the US military that now relies heavily on the use of spaced-based equipment for communicating with forces and detecting foreign military activities, from troop movements to missile launches. The Pentagon report shows China is preparing its forces to wage not only a "Desert Storm-level" of regional conflict, but a 21st-century high-tech war.[32] Since China did not sign the ABM Treaty and the Outer Space Treaty allows conventional arms, such as lasers, to be placed in space, in reality China is free to build GBLs, ABLs and SBLs systems as ASAT weapons. Ample reports exist of China developing ground-based lasers designed to destroy satellites and China’s manned-space program advancements would help provide the delivery systems needed to place SBLs in orbit.[33]

Scenario Two. In Lt Col Baum’s paper entitled, “Defiling the Altar: The Weaponization of Space,” he portrayed a future fictitious limited war in 2011 between the US and China for the

Spratly Islands.[34] He described how preemptive, parallel (or near simultaneous), strategic attacks on downlink facilities from US satellite systems and direct attacks on US satellites virtually crippled the ability of the Joint Warnings Indications Center (JWIC) at the Pentagon to provide surveillance information.[35] Without intelligence, reconnaissance and surveillance information from space to help provide global awareness, political and military commanders would lose information superiority over the Chinese and be unable to make the most effective command and control (C^2) decisions. In addition, Lt Col Baum inferred that Chinese GBLs or SBLs may engage and negate various sensors and satellite systems, including the Defense Support Program or DSP (missile launch detection), DMSP and the Defense Satellite Communications System or DSCS (communications). If DSP's missile launch detection equipment were rendered inoperable, then the US would lose part of its early warning capability of launched SCUD-type or ICBM missiles. If one or both of the DMSP satellites were destroyed, then cloud cover, atmospheric moisture, temperature and other essential weather information needed to reduce the fog and friction of war would be unavailable to US warfighters. And if DSCS satellites were destroyed, then the US would lose some secure communications assets and suffer from degrades in its ability to transmit high-priority C^2 messages to battlefield commanders. Even if civilian communications systems were unaffected by attacks on military satellites and were available in a war, they're unable to encrypt information to provide secure communications and would still be vulnerable to future attacks. Also, if the US military is ever forced to significantly rely on commercial space assets (such as Loral Orion for rooftop-to-rooftop communications for the US Army and DoD) to plan and execute future military actions, access to and control of the civilian space assets may impose costly constraints and restraints on military courses of action. This futuristic limited war illustrates how vulnerable and dependent the US has become on space power to conduct military operations and enhance terrestrial warfighting capabilities.

Emerging Laser ASAT Weapon Threats

The proliferation of advanced laser technology and the commercial availability of high-powered laser systems make laser ASAT weapons a significant threat to US satellites. For example, US satellite vulnerabilities to lasers were already demonstrated in 1997 during the test firing of ground-based MIRACL laser against a US satellite that damaged its sensors after a brief exposure to the beam.[36] In addition, several laser companies, such as Ferranti Photonics Limited, sell kilowatt power CO_2 lasers approaching the comparable laser ASAT systems described above.[37] Almost any high-power industrial laser used for precision cutting and welding, depending upon wavelength, can be turned into a possible laser ASAT weapon with the right optics, target acquisition, target tracking and beam steering controls.

In addition to industrial lasers converted to weapons applications, General Richard B. Meyers, former Commander-in-Chief of US Space Command, reported that the US is susceptible to the growing threat to US military satellites from "laser dazzlers."[38] With a bright burst of light, laser dazzlers can blind optical systems or overload a satellite's optics to prevent it from collecting images, but do not necessarily destroy the satellite.[39] Depending on the ASAT attack effect and the ability to assess and verify the inflicted damage, the attack may constitute a "soft or hard kill" on US space assets. Fortunately, the damage may be reversible in some cases. Dazzlers take denial and deception to the next level and may also negatively impact electro-optical intelligence and other systems. General Myers predicted adversaries may have the capability to use laser dazzlers to achieve "soft or hard kills" against US spacecraft within the next five to eight years, and cautioned that it could be sooner.[40]

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Part 5

Conclusions

> *The art of war teaches us to rely not on the likelihood of the enemy's not coming, but on our own readiness to receive him; not on the chance of his attacking, but rather on the fact that we have made our position unassailable.*
>
> — Sun Tzu[1]

This research project has discussed how an adversary's exploitation, employment and engagement of laser antisatellite weapons, coupled with technological laser developments, may negatively impact the US ability to use space power to enhance terrestrial warfighting capability. After describing a laser's attractive ASAT weapon characteristics, key laser weapon lethality factors were explained in terms or their relevance to attacking satellites. The laser lethality factors related the significance of several central laser weapon parameters, such as range, pointing jitter, atmospheric attenuation, dwell time and target coupling. How ground-, air- and space-based lasers can be employed effectively against space assets to inflict "soft and hard" satellite kills were also briefly discussed. Next, applicable US treaties and political considerations concerning the development and use of laser ASAT weapons were presented. Finally, unclassified sources were used to assess the current level of laser weapons threat to US security and space assets and how adversaries may employ laser ASAT weapons.

Given the looming threat of laser ASAT weapons, US space assets and space dominance are in jeopardy as the US military continues to migrate key intelligence, surveillance and reconnaissance, strategic and theater level warning, weapon's guidance, communications, command and control, environmental monitoring functions and scientific platforms to space.[2] The US advances in weapons technology, such as smart GPS guided munitions, and reliance on space to enhance warfighting capabilities, such as reconnaissance satellites for target selection, now makes the US vulnerable to attacks by potential adversaries if our access and use of space is denied or degraded. Due to the overwhelming military advantage US space power "brings to the fight," any serious opponent to the US knows it cannot win a conventional war, or nuclear war, without destroying US satellite systems.[3] By destroying US satellites, adversaries can physically and psychologically leave the US deaf, dumb, blind, crippled and disoriented. Any disruptions to military access to space could endanger American military and commercial activities as US reliance on space assets has increasingly become a strategic center of gravity, a capability from which the US derives its freedom of action, physical strength, capability and will to fight.[4] Space-based systems have clearly become indispensable to US national security, but US space dominance is no longer a given.

In conclusion, technological developments and the proliferation of advanced laser technology to US adversaries' threatens US space power by possibly degrading or negating the US ability to control and use military and commercial satellites. Exploitable advanced laser technologies in the form of adaptive optics, phase conjugation, diode pumping of lasers, thin membrane optics and high-power laser systems puts US space power and warfighting capability in jeopardy. According to *Joint Vision 2010*, "Our most vexing future adversary may be one who can use technology to make rapid improvements in its military capabilities that provide asymmetrical counters to US military strengths."[5] As some nations are on the verge of or may already possess lasers capable of attacking US satellites, when will adversaries have the political will to use their laser ASAT weapon capabilities? The strategic environment changes quickly and the US has recently seen relations with Russia and China deteriorate.[6] Once adversaries possess both the will and capability to use laser ASAT weapons against over 700 US space assets, then how difficult will it be to shape the international environment, create conditions favorable to US interests and global security, respond to aggression and prepare now for attacks against US space power?[7]

Notes

[1] Sun Tzu, *The Art of War*, edited by James Clavell (New York, NY: Delacorte Press, 1983), 39.

[2] Bell, *Weaponization of Space: Understanding Strategic and Technological Inevitabilities*, 7.

[3] Stratfor, "National Missile Defenses: Fighting the Last War."

[4] Bell, *Weaponization of Space: Understanding Strategic and Technological Inevitabilities*, 7.

[5] John M. Shalikashvili, *Joint Vision 2010* (Washington, D.C.: Chairman of the Joint Chiefs of Staff, 1997), 10.

[6] Stratfor, "National Missile Defenses: Fighting the Last War."

[7] Mehuron, "Space Almanac 1999," 28; John M. Shalikashvili, *National Military Strategy* (Washington, D.C.: U.S. Government Printing Office, 1997), 1.

Appendix A

Some Types of Directed Energy Antisatellite Weapon Systems

> *Directed energy weapons will have widespread application over the next few decades.*
>
> — New World Vistas[1]

Scientists and military professionals have given directed energy systems much attention because there are many potential military applications, especially in the area of weapons. A directed energy weapon (DEW) must be able to generate energy, direct it onto a target, propagate it through air and space to the target, and inflict some lethal damaging effect on the target. Here we'll briefly describe and evaluate four leading DEWs for potential use as antisatellite weapons: electromagnetic pulse (EMP), high-powered microwave (HPM), neutral particle beams (NPB) and lasers.[2]

Electromagnetic Pulse

An EMP is a sudden, high-intensity burst of broad-band electromagnetic radiation travelling at the speed of light and can be used as an ASAT weapon. Due to the intense electric and magnetic fields generated by the EMP, unprotected electrical and electronic equipment can be damaged through circuit malfunction, memory loss and overheating and melting over a large target area.[3] Any system containing semiconductor electronics, including space platforms, could be shut down or burned out by an EMP burst unless protected by heavy, expensive electrical and magnetic shields, well designed electrical filters and careful grounding. The source of the EMP dictates the range of electromagnetic frequencies emitted and possible lethal damage. An EMP can be produced through a nuclear explosion or by conventional means. For instance, the high altitude burst of a nuclear weapon can produce an intense EMP with strong low–frequency components (below 100 MHz) due to the relatively long duration of the explosion.[4] In 1962, for example, a high altitude burst disrupted a number of satellites in orbit when the US detonated a nuclear weapon in space (Starfish).[5] The detonation of a small nuclear weapon in the upper atmosphere could cause widespread paralysis of the US's critical electronic infrastructure and cripple its military ability to wage war.

In addition to nuclear bomb EMP sources, conventional EMP devices built with explosively driven, high-power microwave technology produce less intense, short nanosecond bursts composed primarily of microwaves with frequencies from 100 MHz to 100 GHz.[6] A conventional EMP device can be constructed using a compact pulsed power source (gigawatt range), an electrical energy converter and a high-power microwave device such as a "vircator" (virtual cathode oscillator).[7] The conventional EMP device offers at least two advantages over nuclear explosion driven EMPs. First, a conventional EMP device can be triggered in a shorter amount of time and can put more output energy into the microwave frequencies above 100 MHz than a nuclear explosion generated EMP. Since many modern electronics operate in these microwave ranges, the conventional driven EMP can inflict great damage. Second, a conventional EMP device can be designed to focus the EMP in a particular direction whereas a nuclear explosion driven EMP emits radiation in all directions. However, even a focused EMP produced by a conventional device would probably only have lethal ranges of hundreds to thousands of meters, of course depending on the strength of the power source and atmospheric absorption.[8]

In evaluating nuclear explosion and conventional driven EMP weapons against satellites, one can note several observations. Due to the indiscriminate nature of nuclear explosion driven EMPs, these weapons would most likely only be appropriate in total war situations of national survival because they offer no flexibility.[9] On the other hand, conventional driven EMP weapons offer some flexibility since the EMP can be somewhat focused in a small region. Both EMP weapons have moderate responsiveness and timeliness since they could be launched on demand (if delivered by some type of intercontinental ballistic missile (ICBM)) and possibly reach enemy satellites in less than 30 minutes.[10] Due to the difficulty in aiming or pointing the EMP burst in a specific direction, EMP weapons are not very precise. Since EMP weapons can simultaneously damage the desired target and friendly satellites, these weapons have low selective lethality. In addition, because the EMP effect is highly situational dependent, such as what type of electrical or electronic equipment is attacked, the damage of an engagement is unpredictable. In sum, limited flexibility, poor precision and unpredictable lethality makes EMP weapons poor ASAT weapons for less than total war.

High-Powered Microwaves

A high-powered microwave (HPM) device also produces electromagnetic radiation travelling at the speed of light that could be used as a weapon against satellites. Although not as strong as nuclear explosion driven EMP weapons, HPM weapons create a narrower band of microwave electromagnetic radiation (MHz to GHz range) by coupling fast, high energy pulsed power supplies to specially designed microwave antenna arrays.[11] Microwaves have the advantage of virtually unimpeded transmission through the atmosphere (all-weather capability) and significant damage capability to modern electronics.[12] Unfortunately, HPM devices are line-of-sight weapons meaning the HPM system must "see" their target to engage. Contrary to most EMP weapons, HPM systems can aim and direct beams defined by the shape of their microwave antenna array, but may require an antenna or array of phased antennas with an area measured in acres.[13] However, even at low powers, HPM weapons are capable of disrupting or jamming communications when pointed at adversary's receiving stations or platforms.[14] Also, the beam diameters for HPM weapons are several meters and do not require extreme pointing and tracking accuracies to inflict significant damage.[15] Extended dwell times (time on target) also make HPM attractive ASAT weapons.

In evaluating HPM weapons against satellites, several observations are evident. If a space-based HPM system were available, the all-weather characteristics and speed of light delivery would make this weapon high in timeliness and responsiveness. However, due to several similarities to nuclear explosion driven EMP weapons and line-of-sight targeting requirements, HPM weapons have low flexibility and precision characteristics. Just as with EMP weapons, HPM weapons have unpredictable selective lethality. In sum, limited flexibility, poor precision and unpredictable lethality make HPM weapons moderate ASAT weapon candidates.

Neutral Particle Beams

Particle beam weapons, whether charged or neutral, depend on exotic technology and have not proven their full capabilities or usefulness as ASAT weapons. Weapons-class particle beams require millions of volts of electrical potential, very powerful steering magnets and long accelerating tunnels. Current technology accelerator devices with these capabilities weigh in the hundreds of tons and require large power sources to operate. In general, particle beams have the potential to penetrate satellites and destroy internal systems, such as electronics, at speeds approaching the speed of light.[16] Let's examine the attributes of charged and neutral particle beams as potential ASAT weapons.

Charged particle beams (CPB), such as negatively charged electrons or positively charged protons, are not necessarily very useful weapons due to their natural limitations. CPBs cannot travel through the atmosphere and into space due to ionization and nuclear interactions, cannot propagate for any appreciable range (only a few kilometers) due to diffusion and cannot be accurately pointed due to the influence of the Earth's magnetic field.[17]

Conversely, neutral (uncharged) particle beams, which cannot be accelerated unless they first exist as a CPB in an accelerator, show more promise as ASAT weapons. A neutral particle beam (NPB) weapon can produce a beam of neutral atomic particles by subjecting hydrogen or deuterium gas to a large electrical charge.[18] The electrical charge produces negatively charged ions that are accelerated through a long vacuum tunnel by a large electrical potential. The electrons are then stripped from the negative ions at the end of the tunnel to make high speed neutral atomic particles that form the NPB. The NPB then proceeds in a straight line once they've been accelerated and magnetically pointed just before neutralization in the accelerator. Since the NPB is virtually invisible and difficult to detect, beam control is challenging. The NPB causes damage to its intended target by delivering its kinetic energy directly into the atomic and subatomic structure of the target, heating and damaging the target from within.[19] Unfortunately, NPBs don't propagate well through the atmosphere due to nuclear interaction effects between the neutral particles and air molecules, but they might achieve useful weapon ranges in space.[20] For example, the beam-experiment-aboard rocket (BEAR) test confirmed basic particle beam physics and possible weapons applications. However, according to the project managers at the Los Alamos National Laboratory, many engineering challenges remain.[21]

Due to the weight, size, power requirements and inherent complexity of a NPB weapon, close evaluation makes this system an unlikely candidate as an ASAT weapon. Even if placed in space, the timeliness and responsiveness of a NPB weapon would be low to moderate as the weapon waited to see the target due to the line-of-sight target restrictions. NPBs are only moderate in flexibility and selective lethality since they can inflict temporary to permanent damage. Since NPBs are strongly affected as they pass through the atmosphere, precise engagement would probably only be achievable if the system were space based and engaged in space-to-space force applications.

Lasers

For many years the laser was touted as a "solution in search of a problem," as most of the early applications remained in the research laboratories.[22] The military was one of the first services to envision the potential uses of lasers in many applications. The early hopes of fielding a high-energy laser weapon have yet to be fully realized by the US, but laser technology has matured rapidly in the last thirty years. For example, the Air Force's Airborne Laser program expects to field an operational high-energy laser to engage theater ballistic missiles in their boost phase early in the 21st century. In addition, some space-based components of the megawatt-class ALPHA laser have been constructed and tested on the ground, but not in space.[23]

The laser has also aided other weapons systems. For example, innovative scientists and engineers used the laser beam to point at a target at the speed of light and generate an aim-point to guide bombs directly to targets. As a type of precision guided munitions, the "precision avionics vectoring equipment" series of laser target designators and laser-guided bombs proved very useful in conflicts from the Vietnam War to Operation ALLIED FORCE.[24] Lasers have also served as highly accurate range finders and the backbone of secure communication systems. In addition, laser spotlights have provided visible and infrared illumination to help improve the use of night vision devices.[25] Even though lasers have found widespread use in the US military, some 30 countries with similar capabilities may also look to lasers to level the military capabilities playing field against US assets, especially space assets.[26]

In briefly evaluating the laser's potential as an ASAT weapon, the laser shows great promise. For example, the laser is highly timely and responsive (i.e., can engage targets within seconds of the decision to take action), it has demonstrated high precision and accuracy (evidenced by Airborne Laser tests), and has shown high levels of flexibility and selective lethality ranging from "lighting the battle space" to burning holes in targets.[27] In addition, ground-based or space-based lasers could be used in a space control role since they can be independently pointed at or possibly relayed by mirrors to attack an adversary's space assets. A space-based mirror system could also serve the dual role of enhancing space-based global surveillance and reconnaissance.[28] Although weapons-class, multimegawatt lasers demand large amounts of power to operate and ground-based applications are affected by weather conditions, such as clouds, they appear as the leading DEW candidate as a future ASAT weapon.

Summary

Table 3 gives a brief summary and comparison of each of the DEWs evaluated in Appendix A based on their capabilities of timeliness (real-time/in-time effect), responsiveness (force application to affect crisis or conflict decisively), flexibility (adaptability to fluid force applications), precision (ability to apply discriminate force accurately) and selective lethality (ability to strike *only* the desired target).[29] Each DEW system; i.e., EMP weapon (small and conventionally triggered), space-based HPM, space-based NPB and lasers, is assessed a capability score of low, medium or high.[30]

Table 3. Summary Evaluation of DEWs as Potential ASAT Weapons

	EMP	HPM	NPB	Lasers
Timeliness	Medium	High	Medium	High
Responsiveness	Medium	High	Medium	High
Flexibility	High	High	Low	High
Precision	Medium	Low	High	High
Selective Lethality	Medium	Medium	Medium	High

Source: Adapted from Lt Col Jamie G. Varni et al., "Space Operations: Through The Looking Glass (Global Area Strike System)," AF ***2025*** Study (Maxwell AFB, AL: Air War College, 1996), 48; Lt Col Robert H. Zielinski et al., "Star Tek—Exploiting the Final Frontier: Counterspace Operations in 2025," AF ***2025*** Study (Maxwell AFB, AL: Air War College, 1996), 53.

Overall, the major drawback of DEWs has been the need for clear weather, but this "Achilles' heel" is virtually eliminated if the DEW is placed in space for space-to-space force applications. Large space-based weapon systems, such as HPM and NPB, are not very practical as ASAT weapons due to their weight, cost, size and large power demands. EMP weapons, on the other hand, lack flexibility, require better precision to limit collateral damage and have poor selective lethality. Therefore, lasers appear to be the best DEW to serve as an adversary's ASAT weapon and are discussed in depth in the rest of this paper.

Notes

[1] USAF Scientific Advisory Board, *New World Vistas: Air and Space Power for the 21st Century*, iii.

[2] Jeffrey R. Barnett, *Future War: An Assessment of Aerospace Campaigns in 2010* (Maxwell AFB, AL: Air University Press, 1996), 42.

[3] Varni, Powers, and Crawford, "Space Operations: Through the Looking Glass (Global Area Strike System)," 27.

[4] Ibid.

[5] Hans Mark, "Warfare in Space," 1984, in *America Plans for Space* (Washington, D.C.: National Defense University Press, 1984), 18.

Notes

[6] Varni, Powers, and Crawford, "Space Operations: Through the Looking Glass (Global Area Strike System)," 28.

[7] Ibid.

[8] Ibid., 29.

[9] Ibid., 30.

[10] US GAO Report, *Ballistic Missile Defense-Information on Directed Energy Programs for FY 1985 Through 1993*, tech. rept. no. GAO/NSIAD-93-182 (Washington, D.C.: Government Publication, 1993), 13.

[11] Varni, Powers, and Crawford, "Space Operations: Through the Looking Glass (Global Area Strike System)," 31.

[12] J. D. Jackson, *Classical Electrodynamics*, 2nd ed. (New York, NY: John Wiley & Sons, Inc., 1975), 271.

[13] Varni, Powers, and Crawford, "Space Operations: Through the Looking Glass (Global Area Strike System)," 32.

[14] Ibid.

[15] Ibid., 33.

[16] Petersen, *Space Control and the Role of Antisatellite Weapons*, 71.

[17] Muolo, *Space Handbook: An Analyst's Guide Vol. 2*, 261.

[18] US GAO Report, *Ballistic Missile Defense-Information on Directed Energy Programs for FY 1985 Through 1993*, 28.

[19] Spacecast 2020, *Force Application* (Maxwell AFB, AL: Air University Press, 1994), 22.

[20] Muolo, *Space Handbook: An Analyst's Guide Vol. 2*, 282.

[21] Petersen, *Space Control and the Role of Antisatellite Weapons*, 71.

[22] Rogers, *Lasers in Space: Technological Options for Enhancing US Military Capabilities*, 6.

[23] Ibid., 5.

[24] Ibid., 6.

[25] Ibid.

[26] Neely and Brahney, "U.S. Laser Weapon Test: 'Star Wars Alive and Well?'"

[27] Varni, Powers, and Crawford, "Space Operations: Through the Looking Glass (Global Area Strike System)," 21.

[28] Ibid., 24.

[29] Ibid., 8.

[30] Ibid., 48.

Appendix B

Laser Definition and Basic Operation

Laser is an acronym and stands for Light Amplification by Stimulated Emission of Radiation.[1] Let's look at what each of these words mean to get an understanding of a laser. Visible light is electromagnetic (EM) radiation in the portion of the EM spectrum visible to human eyes; however, lasers are not limited to this small range and span from the ultraviolet to the infrared. Radiation is the process by which an atom or molecule emits energy. For example, the light from an incandescent light bulb radiates light by passing electrical current through a wire filament to heat the molecules of the wire and transfer energy to them.[2] Then the wire molecules lose energy by emitting the radiation and giving off light in the process. Conversely, atoms or molecules can gain energy through the reverse process of absorption. For instance, when the sun shines on human skin, the skin feels warm as some of the sunlight is absorbed.

Due to the wave-particle duality of nature, light behaves as a wave and as small "bundles" or "packets" of particles known as photons. Light as photons are then produced or absorbed in discrete (specific) wavelengths or frequencies when atoms transition from higher-to-lower or lower-to-higher states or levels of internal energy.[3] The laser operates on the phenomenon of stimulated emission, where a photon encounters an atom in a higher internal energy state and incites the emission of another, duplicate photon. For the laser then to generate a very narrow beam of single color (monochromatic) light, the amount of light or number of photons must be amplified, usually by multiple passes through the lasing medium. Light amplification then occurs when the rate of stimulated emission exceeds absorption.[4]

For any laser to operate, it must have three basic parts: an active lasing medium, a means of excitation and an optical feedback cavity for light amplification. Almost any media in any of the three states of matter—solid, liquid or gas—can serve as a lasing medium. Some means of excitation, such as electrical discharges or chemical reactions, provides the energy needed to excite atoms in the lasing medium to reach higher, excited internal energy states from which they can emit photons through stimulated emission.[5] And finally, in the simplest form, sufficient light amplification to achieve lasing occurs in optical cavities created by a pair of mirrors. These mirrors are specially designed to keep most of the emitted photons in the cavity while allowing some photons to escape to form the actual laser beam. Many types of lasers exist, such as gas, semiconductor, liquid, chemical, excimer and free electron lasers, and have several desirable ASAT weapons characteristics.

Notes

[1] Donald C. O'Shea, W. Russell Callen, and William T. Rhodes, *Introduction to Lasers and Their Applications* (Reading, MA: Addison-Wesley Publishing Co., 1978), 56.

[2] Muolo, *Space Handbook: An Analyst's Guide Vol. 2*, 229.

[3] Ibid., 231.

[4] Ibid., 236.

[5] Ibid., 238.

Glossary

λ	wavelength
nm	nanometers (0.000000001 or 10^{-9} meters) [length]
μm	microns (0.000001 or 10^{-6} meters) [length]
ABL	air-based laser
ABM	anti-ballistic missile
ABMT	Anti-ballistic Missile Treaty
ACSC	Air Command and Staff College
AFB	Air Force Base
AFIT	Air Force Institute of Technology
AO	adaptive optics
ASAT	antisatellite
AU	Air University
AWC	Air War College
BEAR	beam-experiment-aboard-rocket
C^2	command and control
CO_2	carbon dioxide
COIL	chemical oxygen-iodine laser
CPB	charged particle beams
CW	continuous wave
DEW	directed energy weapon
DF	deuterium-fluoride
DMSP	Defense Meteorological Support Program
DOD	Department of Defense
DSCS	Defense Satellite Communications System
DSP	Defense Support Program
EM	electromagnetic
EMP	electromagnetic pulse
GBL	ground-based laser
GEO	geosynchronous earth orbit (22,300 miles)
GHz	gigahertz (1 x 10^9 hertz) [frequency]
GPS	Global Positioning System
Hertz (Hz)	unit of frequency (1/sec)

HF	hydrogen-fluoride
HPM	high-power microwave
ICBM	intercontinental ballistic missile
intensity	power divided by area measured in Watts/cm^2
Joule (J)	unit of energy [energy]
JWIC	Joint Warnings Indications Center
laser	light amplification by stimulated emission of radiation
LEO	low earth orbit (60-300 miles)
LGB	laser-guided bombs
LSC	laser supported combustion
LTD	laser target designators
MEO	medium earth orbit (300-22,300 miles)
milliradian	angle measure equal to 0.057 degrees [angle]
MHz	megahertz (1×10^6 hertz) [frequency]
nanosecond	nanosecond = 1×10^{-9} seconds [time]
Nd	neodymium
Nd:YAG	neodymium yttrium aluminum garnet
NPB	neutral particle beam
OPP	other physical principles
PGM	precision guided munition
PLA	Peoples Liberation Army (China)
prf	pulse repetition frequency
radian	angle measure equal to 360 degrees/2π or 57.3 degrees
SCUD	medium range missile
SBL	space-based laser
SBS	stimulated Brillouin scattering
solid angle	subtended area/radius^2
SPOT	*System Pour l'Observation de la Terre*
TMD	theater missile defense
US	United States of America
USAF	United States Air Force
vircator	virtual cathode oscillator
Watt (W)	unit of power (Joule/second) [energy/time]

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

microwave. Any electromagnetic radiation having a wavelength in the approximate range from one millimeter to one meter, the region between infrared and short wave radio wavelengths.

satellite. Any object, manmade or natural, that orbits around another more massive body due to the attraction of gravity.

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