SPACE POLICY FOR LASER IMAGING OF FOREIGN SPACECRAFT

by

PAUL S. IDELL
Major, USAF

NAVAL WAR COLLEGE
Newport, RI

March 1992

DISTRIBUTION LIMITED TO U.S. GOVERNMENT AGENCIES ONLY: SPECIFIC AUTHORITY OPNAVINST 5510.48 SERIES; MARCH 1984. OTHER REQUESTS FOR THIS DOCUMENT MUST BE REFERRED TO PRESIDENT, NAVAL WAR COLLEGE, CENTER FOR NAVAL WARFARE STUDIES, NEWPORT, RI 02841-5010.

SPACE POLICY FOR LASER IMAGING OF FOREIGN SPACECRAFT

EXECUTIVE SUMMARY

Current U.S. Department of Defense policy prohibits the laser illumination of any spacecraft without explicit permission to do so from the satellite's owner. This policy places limitations on the ability to evaluate emerging laser imaging technologies for routine surveillance and imaging of foreign spacecraft. The purpose of this study is to identify and evaluate satellite imaging regimes which admit the application of ground-based laser imaging. To do this a review of pertinent aspects of space law, U.S. policies, and current DOD procedures for controlling the emission of laser energy into space is conducted. Next, the laser illumination requirements for four proposed satellite imaging techniques are reviewed, and their threat to spacecraft components is assessed. From this assessment, it is concluded that while these laser imaging techniques present an in-band damage threat to many earth-viewing optical sensors, they do not threaten the normal operation of other, non-optical satellites. Based on these results, modifications to the current DOD laser illumination policy are drafted and evaluated, together with the current policy, on the basis of their ability to (1) protect U.S. space assets, (2) promote international cooperation in space, and (3) preserve future U.S. freedom of action in space. It is concluded that cooperative, protective measures worked out between the satellite owner/operators and the laser operators to reduce the vulnerability of spaceborne optical sensors may be required before the routine operation of ground-based laser imaging systems against foreign satellites will be accepted.

ADVANCE RESEARCH PROJECT CERTIFICATION

PROJECT TITLE

SPACE POLICY FOR LASER IMAGING OF FOREIGN SPACECRAFT

STUDENT NAME(S)

PAUL S.IDELL
Major, USAF

I/we submit this paper to the Director of the Advanced Research Program in partial satisfaction of the requirements of the Center for Naval Warfare Studies.

Signature: Paul Idell
Signature:
Signature:
Signature:
Full Name of Faculty Advisor: Stephen O. Fought
Signature:
Academic/Staff Title: Dir, Defense Analysis Course
NSDM

Per Naval War College Research Guide, I certify that this paper is substantively acceptable, and that this manuscript is free of typographical, spelling, and other grammatical errors and is ready for evaluation.

Date: 17 Mar 92

Advisor's Signature:

Enclosure (3)

ABSTRACT

Current U.S. Department of Defense policy prohibits the laser illumination of any spacecraft without explicit permission to do so from the satellite's owner. This policy places limitations on the ability to evaluate emerging laser imaging technologies for routine surveillance and imaging of foreign spacecraft. The purpose of this study is to identify and evaluate satellite imaging regimes which admit the application of ground-based laser imaging. To do this a review of pertinent aspects of space law, U.S. policies, and current DOD procedures for controlling the emission of laser energy into space is conducted. Next, the laser illumination requirements for four proposed satellite imaging techniques are reviewed, and their threat to spacecraft components is assessed. From this assessment, it is concluded that while these laser imaging techniques present an in-band damage threat to many earth-viewing optical sensors, they do not threaten the normal operation of other, non-optical satellites. Based on these results, modifications to the current DOD laser illumination policy are drafted and evaluated, together with the current policy, on the basis of their ability to (1) protect U.S. space assets, (2) promote international cooperation in space, and (3) preserve future U.S. freedom of action in space. It is concluded that cooperative, protective measures worked out between the satellite owner/operators and the laser operators to reduce the vulnerability of space-borne optical sensors may be required before the routine operation of ground-based laser imaging systems against foreign satellites will be accepted.

PREFACE

Even though I have worked on the research and development side of space surveillance for the better part of the past fifteen years now, it wouldn't have occurred to me to study a problem such as this while at the Naval War College. I wish to thank Colonel L. John Otten, of the USAF Phillips Laboratory, for originally suggesting this problem to me as an Advanced Research Project, and for continued, personal interest he has shown. I also wish to acknowledge my many dedicated colleagues, both in and out of the military service, who have contributed to this study. In particular, I would like to thank Lt. Colonel John Rabins, AFSPACECOM/DOJ, for his detailed review of the manuscript and thank Colonel Ted Mervosh, SAF/SX, for conducting an additional security review. Finally, and most importantly, I would like to thank Cindy and Philip for their support and understanding over these past few months.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

FIGURE PAGE

LIST OF ACRONYMS

ABM	Anti-Ballistic Missile
AFSPACECOM	Air Force Space Command
AMOS	Air Force Maui Optical Station (formerly, ARPA Maui Optical Station)
ARPA	Advanced Research Projects Agency
ASAT	Anti-Satellite (Weapon)
BMD	Ballistic Missile Defense
CCD	Charge-Coupled Device
DDR&E	Director of Defense Research and Engineering
DMA	Dangerous Military Activities
DOD	Department of Defense
em	Electromagnetic
HST	Hubble Space Telescope
LCH	Laser Clearinghouse
LRS	Laser Ranging Station
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NTM	National Technical Means (of Verification)
OST	Outer Space Treaty
ROE	Rules of Engagement
SALT	Strategic Arms Limitation Talks
SDIO	Space Defense Initiative Organization
SPADOC	Space Defense Operations Center
SPOT	Systeme Probatoire de la Terre
USSPACECOM	U.S. Space Command

ENGINEERING UNITS AND ABBREVIATIONS

Engineering Unit	Abbreviation
centimeter	cm
hertz	Hz
joules	J
meter	m
pulses per second	pps
radians	rad
seconds	s
steradian	sr
watt	W

Prefixes for Engineering Units	Value	Abbreviation
pico	10^{-12}	p
nano	10^{-9}	n
micro	10^{-6}	µ
milli	10^{-3}	m
one	1	
kilo	10^{3}	k
mega	10^{6}	M
giga	10^{9}	G
terra	10^{12}	T

SPACE POLICY FOR LASER IMAGING OF FOREIGN SPACECRAFT

CHAPTER I

INTRODUCTION

As a matter of policy, the U.S. Department of Defense prohibits its laser test sites from intentionally illuminating any spacecraft without the explicit permission to do so from the satellite's owner. While this policy does not prevent the testing of laser techniques against cooperative U.S.-owned satellites, the policy does limit our ability to test laser techniques against the (foreign) space threat for which they are being developed. Recent advances in laser technology and ground-based electro-optical instrumentation offer to revolutionize U.S. situational awareness in space with the ability to remotely inspect foreign spacecraft in orbit with unprecedented levels of detail. The current DOD laser policy, therefore, implicitly limits the U.S. opportunity to capitalize on current technical capabilities and threatens to constrain the freedom of action of its space forces in the future.

An introduction of lasers for satellite imaging at this time may, however, conflict with a well-established norm of behavior which avoids interfering with the operation of foreign spacecraft. The principal challenge in framing a workable policy advocating laser imaging of satellites, then, amounts to balancing the interests of improved military capabilities in space with lasers against the possible negative consequences resulting from their introduction.

Problem

The objective of this paper is to identify and evaluate satellite imaging policy regimes which will permit the widest application of laser imaging technology consistent with the broader scope of U.S. national interests in space. It is hoped that a better appreciation for the policy background affecting laser illumination, together with the technical factors governing the application of laser imaging to satellites, will help guide future space policy developments in this area.

The scope of this study is limited to routine, peacetime applications of ground-based laser imaging. This is done because most of the policy questions concerning laser illumination of satellites arise when laser techniques are applied in peacetime. That is, since laser use is not an internationally banned activity, any nation may apply such measures in its own defense--even in space against satellites. During peacetime, however, the intentional laser illumination of foreign spacecraft may be viewed as a harmful act, possibly provoking an undesirable response from the satellite's owner. The challenge in this study, then, is to identify situations (operational regimes) where laser imaging could be used in routine, peacetime surveillance of space without unnecessarily or unintentionally raising international tensions.

This paper considers the application of laser imaging techniques from terrestrially-based observatory stations only--that is, from observatories on the ground, at sea, or in the air (but not in space)[1]. Ground-based lasers are an issue of intense current interest, in the civil sector as well as the military. And, while space-based laser imaging systems may possess a number of technical and operational advantages over terrestrially based stations, earth based systems will remain of high interest for the foreseeable future. Ground-based stations are a natural proving ground for new innovations in laser technology (ground-based stations provide easy access for testing and evaluation), and experience has shown that ground-based stations have retained significant operational value. The interest in constructing large ground-based astronomical observatories, for example, has accelerated since the advent of space-based observatories such as the Hubble Space Telescope.[2]

---

[1] Hereafter, lasers situated terrestrially are referred to as "ground based."

[2] Buddy Martin, John M. Hill, and Roger Angel, "The New Ground-Based Optical Telescopes," Physics Today, March 1991, pp. 22-23.

Although satellite imaging with lasers is admittedly a very narrow and and somewhat technical concern, analysis of this topic addresses interrelationships which are of great interest to a number of groups involved in the space policy process. First of all, drafters of space policy will benefit from an increased appreciation of the interplay between laser technology, operational concerns, and international relations in space. Second, the study provides space operators with a deeper understanding of the utility of laser imaging technology allowing him to factor such capabilities into plans and requirements for future upgrades to operational systems. Finally, this study is beneficial to members of the DOD research and development community who are better able to assess opportunities for transitioning currently available technology, and are better able to evaluate investment alternatives for future research and development in this area.

Approach and Outline of the Paper

To explore possible policy regimes for laser illumination of satellites, one needs to develop a detailed appreciation for the issues affecting the laser policy. Chapter II describes the capabilities of emerging ground-based laser imaging technology and attempts to establish the utility of this technology to U.S. defense interests in space. In essence, this chapter answers the question "What's to be gained by lasing satellites in the first place?" Also presented here is a glimpse at expanding civil applications of lasers in space which run concurrently with an expanded U.S. laser presence in space.

Chapter III presents a survey of the current ground rules limiting the application of laser illumination of satellites. Here, pertinent aspects of international space law and U.S. space policy are reviewed. The current DOD procedures for limiting the emission of laser light into space are also summarized, providing the basis for further considerations of alternate operating procedures and policies (presented in chapter V). Based on considerations of U.S. space policy, current operating guidelines, and space law, three criteria for the evaluation of alternative laser policy regimes are drafted.

The most significant technical issue arising from the considerations of chapter III is the definition of the term *harmful interference*: "Under what conditions would laser imaging of foreign satellites be considered harmful to their normal operation?" Chapter IV attempts to answer this question by considering the laser power levels needed to image satellites from the ground and the effect that this illumination might have various spacecraft components.

Using the technical results of chapter IV, the current operating guidelines for laser illumination of foreign satellites is evaluated in chapter V together with three alternative sets of guidelines for the peacetime application of ground-based laser imaging. Here, the operating guidelines are posed as four sets of peacetime rules of engagement (ROE) for laser imaging which are evaluated on the basis of the policy criteria offered at the conclusion of chapter III.

Finally, chapter VI summarizes the main conclusions drawn from the study.

Contributions

This report offers three major contributions to the study of laser imaging policy. First, the paper brings together and discusses the various disparate issues--U.S. space policy, space law, and operational controls together with the technical considerations of imaging laser requirements and satellite vulnerabilities--which must be factored into the development of such a policy. Second, this paper presents the first quantitative assessment of satellite vulnerabilities to laser imaging from the ground. From this assessment, one can begin to distinguish which satellites are threatened, at what illumination levels, and at what laser wavelengths. A number of protective measures which may reduce the sensitivity of satellite-borne optical sensors are proposed, some of which may actually facilitate a wider acceptance of ground-based laser imaging. Finally, emerging from these considerations, a number of laser imaging regimes are proposed which span a number of possible U.S. military approaches to introduce laser imaging. The principal insight gained here is the role that protective measures and international cooperation (tacit or explicit) may play in reducing real and perceived threats arising from the use of laser techniques to image foreign satellites.

CHAPTER II

GROUND-BASED LASER IMAGING: A REVOLUTION AT THE THRESHOLD

GROUND-BASED LASER IMAGING CAPABILITIES

Some of the principal attractions of using lasers for ground-based imaging result from the physical properties of laser light. Lasers are excellent sources of short wavelength, coherent electromagnetic (em) radiation. Laser beams are extremely narrow (on the order of milliradians or less) and intense, making them very effective target designators or imaging illuminators. This is especially significant for the optical tracking and imaging of low earth satellites which are unobservable when in the earth's shadow. Further, laser illumination can be used to augment whatever naturally occurring illumination exists, direct sunlight or earthshine, for example. Their narrow beams, however, make lasers generally ineffective for wide-area surveillance applications where large angular fields must be scanned. Consequently, the acquisition of satellites for the purposes of laser illumination requires either extremely good orbital element sets[1] or a handover from a wide beam tracking radar.

The fact that lasers operate at extremely high em frequencies (about 3×10^{14} hertz) means that they may be used to carry very high bandwidth impressed signals. This is a primary feature sought in fiber-optic communications, for example. When properly exploited, this same property results in very high precision laser ranging systems and other laser radar applications (including laser imaging) which use signal modulated pulse trains.

---

[1] As a point of reference, a 100 microradian field-of-view acquisition telescope may be adequate for acquiring satellites whose orbital element sets (elsets) can be obtained from a NASA computer bulletin board. These elsets are updated every few days through a direct AUTODIN link to the NORAD Space Computation Center. Telephone conversation with Lieutenant Colonel John Rabins, USAF Space Command (DOJ), 20 February 1992.

HISTORICAL BACKGROUND

Although the use of lasers for illuminating space objects quickly followed the first demonstrations of a working laser device,[2] the use of lasers for assisting in the formation of highly detailed images of earth-orbiting satellites has been, however, a much more difficult proposition. Because of random temperature fluctuations in the atmosphere, light (e.g., reflected sunlight or even laser light) reaching ground-based telescopes from space objects is severely corrupted. These fluctuations, generally referred to as atmospheric turbulence, produce the familiar twinkling of stars. As a result, images formed by even the highest quality ground-based telescopes can achieve no better that about five microradians (or, one arc-second) of angular resolution. This limiting angular resolution corresponds to a smallest-resolvable feature size of about five meters on a satellite at 1000 kilometers range, or a one meter feature at a range of 200 kilometers. Consequently, unless special measures are taken, satellites--which, typically, have a maximum dimension on the order of five meters--cannot be resolved with high detail from the earth no matter how they are illuminated. For the purposes of space object identification and satellite mission assessment, a desired image resolution of 10 centimeters (four inches) is often quoted.[3] Achieving this resolution at any satellite altitude is problematic unless something can be done about the problem of atmospheric turbulence.

Laser imaging techniques were considered in two U.S. National Academy of Sciences summer studies of 1966 and 1967 which dealt with the more general problem of imaging

---

[2] Theodore H. Maiman of Hughes Research Laboratory in Malibu, CA reported the operation of the world's first laser in 1960. The first laser echoes from the moon were reported in 1962, followed by the first laser ranging tests against satellites in 1964. See discussion on laser ranging, below.

[3] The figure of 10 cm is often attributed to a study conducted by Neil Anderson, now deceased, at the Aerospace Corporation in the early 1970's. In this study, blurred photographs of satellite models exhibiting different visual quality were shown to a number of photointerpreters, who were asked to identify various features in each of the blurred photographs. Results of study were summarized in a graph which plotted the number of recognizable satellite features versus the image resolution characterizing the blur in each photograph. The resulting curve exhibited a "knee" at a feature resolution of 10 cm. The author is indebted to Mr. Steven Pease of Air Force Space Command (INY) for a description of this study.

objects in space through the earth's atmosphere,[4] and certain proposed techniques were evaluated over long optical paths.[5] A number of proposals for imaging satellites with lasers were developed and evaluated in the laboratory in the early 1970's,[6] but no operating systems of this type were constructed. At the same time, alternative optical imaging techniques which did not require laser illumination were being offered.

During the 1970's DOD research into ground-based satellite imaging concentrated in the new area of adaptive optics,[7] which promised greater future applications in the area of high energy laser beam weapons. A demonstration adaptive optics system, called the Compensated Imaging System, was constructed for the Advanced Research Projects Agency (ARPA)[8] by Itek Corporation and installed at the ARPA Maui Optical Station in 1982 for the purpose of demonstrating its capability to image satellites in earth orbit. The imaging system, whose performance specifications were recently declassified,[9] is currently operated on Maui by the USAF Phillips Laboratory. The system, whose design predates similar astronomical systems being considered today by about 15 years, operates by correcting the deleterious effects of atmospheric turbulence in real time. Unfortunately, experience with this instrument has shown that its ability to correct for atmospheric turbulence is limited by the brightness of the object

---

[4] National Academy of Sciences, <u>Restoration of Atmospherically Degraded Images</u>, Woods Hole Summer Study (Washington, D.C.: 1966).

[5] J.W. Goodman, et. al., "Experiments in Long Distance Holographic Imagery," <u>Applied Optics</u> vol. 8, 1969, 1481-1486.

[6] W.B Bridges, et. al., <u>Space Object Imaging Techniques</u>, Final Technical Report Under Contract DAAH01-73-C-0629 (Malibu, CA: Hughes Research Laboratory, 1974), pp. 205-236.

[7] J.W. Hardy, "Adaptive Optics: A New Technology for the Control of Light," <u>Proceedings of the IEEE</u> vol. 66, 1978, p. 651.

[8] The agency is now called the Defense Advanced Research Projects Agency (DARPA).

[9] USAF Phillips Laboratory Commander, "Letter Change No. 2 to the Air Force Maui Optical Station (AMOS) Security Classification Guide, 9 Aug 89," 22 July 1991.

being imaged. Further, since some light from the object is used to sense atmospheric distortions, the amount of light available for image formation is much reduced.

LASER IMAGING CONCEPTS

Laser Guide Stars. Recently, there has been much interest in the astronomical[10] and military[11] communities in generating artificial guide stars to improve the performance of ground-based telescopes. Artificial guide stars are produced by transmitting a laser beam into the atmosphere in the direction of the space object to be imaged. Light scattered back from the atmosphere produces a laser "beacon" which can be used to calibrate an adaptive optics system.[12]

Depending on the wavelength of the laser and the atmospheric particulates producing light scattering, laser guide stars are classified as either of the "Rayleigh" or "Sodium" type. Sodium guide stars are produced by transmitting short laser pulses at 0.589 μm wavelength. These pulses are used to excite sodium atoms at altitudes between 80 and 110 kilometers in the atmosphere, producing the sodium guide star beacon.[13] Rayleigh guide stars, on the other hand, are produced by non-resonant scattering off of nitrogen and oxygen molecules in the lower atmosphere. In principle almost any short wavelength laser may be used to produce a

---

[10] L.A. Thompson and C.S. Gardner, "Experiments on Laser Guide Stars at Mauna Kea Observatory for Adaptive Imaging in Astronomy," Nature vol. 328, 1987, pp. 229-231

[11] R.Q. Fugate et al., "Measurement of Atmospheric Wavefront Distortion Using Scattered Lidght from a Laser Guide-Star," Nature vol. 353, 12 September 1991, pp. 144-146.

[12] With adaptive optics, a wavefront sensor is used to sense the instantaneous distortions in the incoming light produced by its passage through a turbulent atmospheric path, such as that experienced by light returning from sunlit objects in space. The measurement made by the wavefront sensor is then used to command a flexible optical element (usually a electronically deformable mirror) which corrects for the sensed distortions in real time. See, for example, R.K. Tyson, Principles of Adaptive Optical Systems, (San Diego, CA: Academic Press, 1991).

[13] C.S. Gardner, "Sodium Resonance Fluorescence Lidar Applications in Atmospheric Science and Astronomy," Proceedings of the IEEE vol. 77, March 1989, p. 408.

Rayleigh guide star, but the shortest visible wavelengths (toward the blue and ultraviolet end of the spectrum) are preferred because scattered light intensity is proportional to the reciprocal fourth power of the laser wavelength.[14] In practice Rayleigh guide stars are produced at altitudes of 4 to 10 kilometers.[15]

Because a laser guide star can be used to calibrate an adaptive optics system, any sunlight (or, other laser light) reflected off a satellite could be used to form an atmospherically-compensated, or corrected, image with the telescope. And, so long as the amount of reflected sunlight available for image formation is sufficient (i.e., the satellite is not in earth shadow), the amount of laser light needed to create the guide star is independent of the satellite altitude--that is, the guide star laser is focussed at some finite range within the atmosphere. Because of beam diffraction, the amount of laser power actually striking the satellite being imaged falls off as the square of the satellite's range. This situation is distinct from that of other laser imaging techniques (see below) which form images by directly and intentionally illuminating the satellite being imaged. This requirement implies that the amount of laser power striking a target satellite must generally increase with target range (or, at the very least stay a constant value for all ranges).[16]

Welsh et. al.[17] have computed laser characteristics needed to generate a sodium laser guide star of sufficient brightness to drive an adaptive optics system for astronomical applications. Welsh calculates that a laser pulse energy of 106 mJ with a pulse length of 69 μs

---

[14] Rayleigh scattering of sunlight causes the daytime sky to appear blue.

[15] Graham P. Collins, "Making Stars to See Stars: DOD Adaptive Optics Work is Declassified," Physics Today, February 1992, p. 18.

[16] See more discussion on this technical point in chapter 4.

[17] Byron M. Welsh, Chester S. Gardner, and Laird A. Thompson, "Effects of Nonlinear Resonant Absorption on Sodium Laser Guide Stars," SPIE Proceedings vol. 1114 , March 1989, (preprint).

will generate a sufficiently bright resonant source to permit the correction of an atmosphere characterized by an atmospheric (phase) coherence length r_0 equal to 18.5 cm. Operating at a pulse repetition rate of 200 Hz for astronomical applications, this laser provides an average of 21 W output power. When applied to low earth orbit satellites, the imaging telescope and its line of sight will slew through the atmosphere increasing the required bandwidth for the adaptive optics system and, consequently, the laser pulse repetition rate by a factor of 10 to 100.[18] Following Welsh's calculations, the pulse repetition rate needed to drive a one kilohertz closed-loop adaptive optics system (i.e., 50 times correction bandwidth Welsh has assumed) would be about ten kilohertz, requiring an output laser power of about 1.06 kilowatts. It should be pointed out that this power figure is not optimized in any way (nor are any of those cited below), but is suggested as a "ball park" figure for purposes of discussion. Operating a sodium laser guide star in conjunction with a low altitude Rayleigh beacon, for example, could balance the wavefront correction task between the two laser systems, reducing the power requirement for the sodium laser.[19] This concept would require the use of two laser colors for atmospheric correction, however. Current guide star lasers used in DOD research are in the 10 to 250 watt class.[20]

Imaging With Direct Object Illumination. Alternatively, satellite images can be formed by directly illuminating them with suitably powerful laser beams; however, because of atmospheric turbulence, some form of atmospheric correction must again be devised. There are three general approaches to accomplishing this with direct satellite illumination. First, the illuminated object may be imaged by a ground-based telescope which does or does not possess

---

[18] Graham Collins, p.21.

[19] *Ibid.*, p. 20.

[20] Telephone conversation with Major John Anderson, U.S. Air Force Phillips Laboratory, Starfire Optical Range, Kirtland AFB, NM, 6 January 1992.

adaptive optics correction. If the telescope contains adaptive optics, the image formed with reflected laser light will be atmospherically corrected. Note that this imaging system may require two lasers--one to flood light the satellite and another to create a guide star to drive the adaptive optics system. If adaptive optics is not used, a number of atmospherically distorted laser images can be digitally processed to create an atmospherically corrected, composite image. With either of these "conventional" laser imaging techniques, the ultimate resolution obtained at the satellite is limited by the diffraction limit of the ground-based imaging telescope. With the size of present day satellite-tracking, ground-based telescopes limited to sizes no larger than 3.5 meters in diameter,[21] the satellite ranges at which high resolution (e.g., less than 10 centimeters object resolution) imagery can be collected is limited to about 630 kilometers using visible wavelength lasers.[22] Recent proposals for large, sparse telescope arrays may offer the opportunity of extending high resolution satellite imaging capabilities by digital post-processing to 4000 km range and beyond.[23]

Ruby lasers (0.694 μm wavelength) have been used at the Air Force Maui Optical Station (AMOS) since the early 1970's to range satellites in orbit. When operated in the "giant pulse" mode (providing up to 80 J of output energy), the AMOS ruby laser[24] has been used to flood illuminate space objects for the purposes of active (laser-light augmented) imaging with ground-based telescopes. In the giant pulse mode, the ruby laser nominally operates with a

---

[21] U.S. Air Force Phillips Laboratory, "Starfire Optical Range," PL/LTE Fact Sheet, 1991.

[22] Diffraction limited object resolution for optical telescopes is calculated from the expression $\Delta x = \lambda R/D$, where Δx is the resolution scale (in meters), λ is the wavelength, R is the range, and D is the aperture diameter of the imaging telescope. For $\lambda = .55 \times 10^{-6}$ meters, R = 630 km, and D = 3.5 meters, Δx is 10 cm.

[23] N.A. Massie, et. al., "Stalking Satellites in High Resolution," Lasers and Optronics, June 1990, pp. 44-50; N.A. Massie, et al, "Low Cost, High-Resolution, Single-structure Array Telescopes for Imaging of Low-Earth-Orbit Satellites," Applied Optics vol. 31, 1 February 1992, pp. 447-456.

[24] AVCO Everett Research Laboratory, AMOS Users Manual, AERLM 1176 (Puunene, Maui HI: 1982), pp. 57-60.

pulse length of one millisecond and a pulse repetition rate of twenty pulses per minute (0.33 pps). In order to compensate for atmospheric distortions (and, possibly, laser coherence effects) which will corrupt the imagery collected in this way, it may be necessary to collect fifty or more flood light images for post-detection image processing. Since the satellite's aspect (when viewed from a fixed position on the earth) changes during a satellite pass, a pulse repetition rate of 10 Hz may be required to permit such image processing options.[25] Thus, an improved AMOS ruby laser operating at 80 J and 10 pulses per second would transmit an average of 800 W power.

A second approach to imaging with direct laser illumination is to sense the backscattered laser energy with a large array of optical detector elements in place of an imaging telescope. A number of groups have suggested imaging concepts which rely on this approach, which can be generally likened to a kind of long range holography.[26] Though the details of each implementation vary, all these techniques require sensing the coherent light field pattern (also known as a laser speckle pattern) in a sampled aperture array. Then, various forms of digital signal processing may be applied to the collected data to reconstruct an image of the laser illuminated object, in effect, correcting for the effects of atmospheric turbulence.[27] A significant potential advantage of laser speckle imaging over those relying on adaptive optics techniques is that large receiver arrays may be constructed without the need for real-time

---

[25] The viewing time for a non-rotating, low-earth orbit satellite may be 5-10 seconds. A laser pulse rate of ten hertz would provide 50-100 snapshots of the satellite before the satellites viewing aspect changes significantly.

[26] Goodman, pp. 1481-1486; Bridges, et al., p. 3; P.S Idell, et al., "Image Synthesis From Nonimaged Laser-Speckle Patterns," Optics Letters vol. 12, 1987, pp. 858-860; J.F. Belsher and D.L. Fried, "Shear Speckle Imaging," SPIE Proceedings vol. 1351, 1990, pp. 604-615; P.S. Idell and J.D. Gonglewski, "Image Synthesis from Wavefront Measurements of a Coherent Diffraction Field," Optics Letters vol. 15, 1990, pp. 1309-1311; Louis Sica, "Estimator and Signal-to-Noise Ratio for an Integrative Synthetic Aperture Imaging Technique," Applied Optics vol. 30, 15 January 1991, pp. 206-213.

[27] P.S. Idell and D.G. Voelz, "Nonconventional Laser Imaging Using Sampled-Aperture Receivers," Optics and Photonics News, April 1992, pp. 8-15 (to appear).

actuating elements. For this reason, it is hoped that effective imaging apertures of ten meters or larger could be economically constructed. A ten meter by ten meter receiver array, for example, could achieve 10 cm satellite resolution out to 4000 km at visible laser wavelength. A twenty meter receiver could image to the same resolution (at the same wavelength) at twice this range, etc. Because no adaptive optics correction is used with the imaging receiver, only a single object illuminating laser is required; however, in the interests of minimizing transmitted laser power, adaptive optics may be required to maintain tight illuminating beams for targets at the greatest ranges.

Though a number of different laser systems (and wavelengths) have been proposed for laser speckle imaging, we will consider a system conceived at the USAF Phillips Laboratory for a partial field demonstration at the Starfire Optical Range later this year.[28] The illuminator laser for this demonstration is a flashlamp-pumped photolytic iodine laser (wavelength of 1.315 μm) producing about 60 J pulses at a rate of 0.5 pps, sufficient for imaging satellites at ranges up to 1000 km without uplink adaptive optics compensation. The laser pulse length is ten microseconds. In order to compensate for laser speckle effects in the imagery produced by such systems, an operational system may require a pulse repetition rate of 10 pps, producing an average output power of 600 watts. Although this figure reflects this particular example system, it is representative of the pulse energy and power required of lasers for other short wavelength implementations and target ranges up to and beyond 1000 km.

Finally, a third approach to imaging by direct illumination borrows from (inverse) synthetic aperture radar concepts originally developed for radar imaging at microwave wavelengths.[29] Following on a history of imaging laser radar developments dating back to the

---

[28] Telephone conversation with Lieutenant Colonel David Stone, U.S. Air Force Phillips Laboratory, Imaging Technology Branch, 20 February 1992.

[29] J.L. Walker, "Range Doppler Imaging of Rotating Objects," IEEE Transactions vol. AES-16, January 1980, pp. 23-52.

late 1960's,[30] the Massachusetts Institute of Technology's Lincoln Laboratory has developed and successfully demonstrated a laser imaging radar at the Firepond Test Facility at the Millstone Hill/Haystack Radar Site in Westford, MA.[31] The system operates by transmitting a series of coded, wideband CO_2 laser pulses. When the illuminated object rotates such that its rotation axis is not aligned with the laser's line of sight, the backscattered laser light contains information which can be manipulated to produce a two-dimensional image of the object (that is, in the range and cross-range dimensions). Because image information is encoded in the collected time and doppler signatures of the laser illuminated object, the achievable image resolution is determined by the bandwidth of the coded pulse and by the number of resolvable doppler bins in the received signal. As a consequence, the image resolution achievable from this technique is not fundamentally limited by the size of the collecting aperture (as was the case with the three laser imaging techniques discussed previously) but rather by the nature of the laser signal waveform used to illuminate the object and the dynamic characteristics of the object itself.[32] Therefore, aside from signal-to-noise considerations which may necessitate larger aperture sizes at long target ranges, the laser transmitter and receiver apertures do not need to be so large that adaptive optics correction is required.[33]

---

[30] Leo J. Sullivan, "Infrared Coherent Radar," SPIE Proceedings vol. 227, 1980, pp. 148-161.

[31] W.E. Keicher, B.E. Edwards, and L.J. Sullivan, "The Firepond Long Range Imaging CO_2 Laser Radar," Optical Society of America Conference on Coherent Laser Radar, Snowmass, CO, 8-12 July 1991 (preprint).

[32] A radar's range resolution is given by the expression c/2B, where c is the speed of light and B is the pulse bandwidth. If the laser radar has an effective operating bandwidth of one gigahertz (10^9 Hz), its image resolution in the range dimension is, theoretically, 15 centimeters. The radar's cross-range resolution--really the resolution orthogonal to the axis of the object rotation--is given by $\lambda/\omega T$, where λ is the wavelength, ω is the apparent rotation rate of the object, and T is the pulse length. Therefore, if the satellite is rotating at one revolution per minute, the best cross-range resolution obtainable by a laser radar operating at 11.2 μm wavelength with a 30 microsecond pulse length is 3.6 meters. The resolution is finer in proportion to the rotation rate for faster tumbling objects, so an object rotating at 10 rpm could be imaged with at best 36 cm cross-range resolution, etc.

[33] The Firepond laser radar currently operates with a 1.2 meter aperture transmitting and receiving telescope. Operating at wavelength of 11.17 micrometers, the laser radar transceiver telescope is not affected by

In an April 1990 rocket test, for example, it successfully imaged a number of deployed payload elements at a range of 750 km.[34] Subsequently, the device has also imaged satellites at ranges of 1500 km.[35] When operated in the imaging mode, the CO_2 Firepond laser (11.17 μm wavelength) transmits a peak energy of 60 J per pulse at 10 pps, producing an average transmitted power of 600 watts. The laser pulse width is 30 μs.

Table I summarizes the principal operating features of the laser imaging techniques discussed above. Due to current technology limitations, the operating range of these devices is limited to satellites in low earth orbit below 2000 km altitude. Though restricted in this way, these approaches permit imaging resolutions of 25 cm (ten inches) or better on more than fifty percent of the former Soviet satellite population.[36]

Although specific lasers have been selected for the purposes of this discussion, other devices could be considered if they operated at a wavelength which is not significantly absorbed by the atmosphere and they meet other performance requirements particular to each laser imaging technique. In aggregate, the lasers listed in the table span a wide wavelength spectrum from 0.589 μm (sodium) to 11.17 μm (CO_2). They operate at a range of laser pulse energies, but all would radiate an average optical power on the order of a kilowatt. By

---

atmospheric turbulence to the extent that shorter wavelength optical systems would be. Consequently, no high-order adaptive optics correction is necessary for this system.

[34] "Firefly Laser Experiment Successful in Measuring Inflatable Decoy Motion," Aviation Week and Space Technology, 23 April 1990, p. 75.

[35] Interview with William E. Keicher, MIT Lincoln Laboratory, Lexington, MA: 3 January 1992.

[36] Rettig P. Benedict, Colonel, USAF (Ret.), "Space Object Identification Challenges and Opportunities," Briefing (Albuquerque, NM: W.J. Schafer Associates, Inc., 22 April 1991).

TABLE I

KEY FEATURES OF PROPOSED LASER IMAGING SYSTEMS

IMAGING TECHNIQUE	LASER WAVELENGTH (μm)	PULSE ENERGY/ AVERAGE RADIATED POWER	ATMOSPHERIC CORRECTION APPROACH	DIRECT OR INDIRECT OBJECT ILLUMINATION	NOMINAL OPERATING RANGE[a] (KM)
SODIUM GUIDE STAR	0.589	106 mJ 1060 W	ADAPTIVE OPTICS	INDIRECT	1100[b]
FLOOD LIGHT	0.694	80 J 800 W	ADAPTIVE OPTICS OR DIGITAL PROCESSING	DIRECT	1300[c]
LASER SPECKLE	1.315	60 J 600 W	DIGITAL PROCESSING	DIRECT	1900[d]
WIDEBAND COHERENT	11.17	60 J 600 W	UNNECESSARY FOR LONG WAVELENGTH OPERATION	DIRECT	1500[e]

a. Approximate maximum range at which 25 centimeters object resolution can be achieved (see other notes below).

b. Assuming a fully-corrected 3.5 meter telescope aperture at an image sensing wavelength of 0.8 micrometers.

c. Assuming full correction (either through adaptive optics or signal processing) of an 3.5 meter diameter telescope at 0.694 micrometers wavelength.

d. Assuming a 10 meter receiving array at 1.315 micrometers wavelength.

e. Interview with W.E. Keicher, MIT Lincoln Laboratory (see text).

Source: See text.

comparison, the U.S. Navy's Mid-Infrared Advanced Chemical Laser (MIRACL), a continuous wave deuterium-flouride device (3.8 μm wavelength) located at the White Sands Missile Range, New Mexico, is reported to have radiated 2.2 megawatts of laser power.[37] After having been mated with the Navy's Sealite beam director, MIRACL is considered by some in Congress to have potential as an antisatellite weapon. Currently, this device cannot be tested against any object in space unless specifically authorized by law.[38] A comparison with the laser powers displayed in Table I shows that MIRACL is about two thousand times more powerful than the lasers being considered for satellite imaging.

MILITARY APPLICATIONS OF GROUND-BASED LASER IMAGING

The near-term military utility of ground-based laser imaging systems essentially follows from their ability to peer into space (under clear weather conditions) and collect high resolution images of objects of interest. When a laser directly illuminates the object, laser light can make up for a lack of naturally occurring light. In somewhat the same way that conventional radar can sense the presence of an object by illuminating it with microwave radiation, the laser imaging system can, at least in principal, form a highly detailed image of distant objects. Whenever it is operationally or economically infeasible to place an optical inspection device in space, then, the ability to correct for atmospheric turbulence now gives one the option of placing the imaging sensor on the ground. See Figure 1.

On the other hand, ground-based laser imaging systems possess some clear drawbacks and limitations. Because these techniques are optical, they cannot penetrate clouds, dust or

---

[37] Paul B. Stares, Space and National Security (Washington, DC: The Brookings Institution, 1987), p. 112.

[38] U.S. Congress, House, Conference Report to Accompany H.R. 2100, National Defense Authorization Act for Fiscal Years 1992 and 1993, Report 102-311 (Washington, DC: GPO, 1991), p. 28.

FIGURE 1

MILITARY APPLICATIONS OF GROUND-BASED LASER IMAGING

RESEARCH AND DEVELOPMENT
- ADVANCED SURVEILLANCE APPLICATIONS
- TREATY VERIFICATION CONCEPTS
- WEAPONS SUPPORT
- COMPONENT TECHNOLOGY VALIDATION

OPERATIONAL SPACE SURVEILLANCE
- SATELLITE IDENTIFICATION/CAPABILITY ASSESSMENTS
- SPACE ORDER OF BATTLE
- ATTACK WARNING
- SPACE TREATY VERIFICATION
- DIAGNOSING SATELLITE MALFUNCTIONS
- ASAT WEAPONS SUPPORT

SATELLITE SENSOR BLINDING WEAPON

Source: See text.

foul weather. Because they are active sensors, the object being imaged can sense that it is being interrogated and, perhaps, take reactive measures. For this reason one would not expect laser imaging devices to successfully operate in a covert fashion for prolonged periods of time. Also, since the targets of interest may, themselves, be carrying optical sensors, the laser illumination could interfere with that optical sensor's operation. The fact that these sensors are located on earth implies they can be made very sophisticated and be easily tended to. On the other hand, because of geometrical viewing constraints--and, unless your imaging device is mobile or transportable--one has to sit and wait for the object to fly overhead. Because satellite orbits are generally very regular and predictable, observing missions can be planned ahead of time (provided, again, the weather holds out).

The United States Space Command (USSPACECOM) is charged with the responsibility to maintain constant surveillance of space for the purpose of detecting, tracking, identifying, cataloging, and characterizing all man-made objects in space.[39] In performing these functions it supports the objective of space control,[40] making assessments and warning of impending attacks on U.S. spacecraft, space order of battle, and intelligence on foreign space systems capabilities. In addition, USSPACECOM surveillance capabilities may support space treaty verification and help to diagnose problems with U.S. spacecraft. The current set of sensors used for space surveillance comprise a network of ground-based radar and optical (including infrared) sensors which provide data from a full-time to part-time (subscription) basis. Without going into details which are considered sensitive, the USSPACECOM ROC identifies limitations of the surveillance network both in terms of timeliness (time between sensor tasking and data receipt from the site) and capability. It cites the need for further technology development to redress network deficiencies.

High resolution imaging will support USSPACECOM surveillance missions by providing detailed physical renderings of foreign satellites. Maintaining the space order of battle, for example, requires classifying all newly launched foreign payloads. While correlating new launches to historic launch profiles (e.g., launch site, orbit inclination, orbital altitude) can be used to make initial assessments of satellite mission, follow-up visual inspection may be needed to monitor physical spacecraft changes which may change the initial threat assessment. Further, for foreign satellite launches that do not fit a standard profile, visual inspection may play a much greater role in assessing the threat and helping to remove any anxiety produced by non-historic launch events. Once the spacecraft mission has been classified and has been determined to be operating properly, periodic monitoring may be

---

[39] U.S. Dept. of Defense, U.S. Space Command, USSPACECOM Required Operational Capability for Space Surveillance (U), USSPACECOM ROC 01-88, 17 June 1988. SECRET

[40] U.S. Dept. of Defense, U.S. Space Command, Doctrine for Space Control Forces, USSPACECOM Pamphlet 2-1, 27 March 1990.

required to ascertain its mission status later in life (i.e., whether it is operating normally, dead, or just "sleeping").

The ability to inspect foreign spacecraft would reduce the role of deception in military space operations[41] and give the United States a greater capability to monitor agreements to limit arms deployments in space. It may, for example, permit the United States to scrutinize new launches for possible space-based CIS antiballistic missile components which would violate the 1972 SALT I ABM Treaty. Further, the employment of a high resolution inspection capability combined with a credible antisatellite capability could have a strong deterrent value. Foreign space powers, knowing the United States possessed the capability to routinely inspect their spacecraft on orbit, may be convinced of the futility of beginning (or continuing) military operations in space. The value of such a capability--to paraphrase Liddell-Hart[42]--is to establish a strategic posture in space so advantageous to U.S. interests that if the situation does not by itself produce the desired outcome, its continuation by the use of force could surely achieve it.

Knowledge of U.S. surveillance capabilities could evoke attempts to make foreign satellites invisible to optical imaging. However, such attempts to make satellites "stealthy" would require additional cost and a risk of compromising the satellite's primary mission. Furthermore, as with the case of terrestrial stealthy measures, techniques which are effective against optical radiation may not be effective in countering other, complementary surveillance and information gathering methods (e.g., radar, infrared).

Satellite imagery may be useful in troubleshooting unidentified problems on U.S. or allied spacecraft (military or otherwise). On board sensors, for example, may not report

---

[41] John M. Collins, Military Space Forces: The Next 50 Years, Congressional Research Service Report 89-578 RCO (Washington, DC: The Library of Congress, 12 October 1991), p. 44.

[42] *Ibid.*

whether a particular shroud or panel has deployed properly. A high resolution imager would help in evaluating the next course of action. Instances involving U.S. military systems periodically arise, where the consequences of such assessments could determine whether or not a replacement spacecraft is launched. USAF ground imaging test sites have also been alerted of the earth fly-by of the NASA Galileo spacecraft which has a mispositioned antenna. Possessing high resolution imaging capabilities and having them available to assist foreign satellite owners may produce good will and foster greater international cooperation in space.

A high resolution imaging capability could prove especially useful in support of a future operational ASAT weapon. Prior to targeting a particular satellite the imaging device could be used to verify that the intended target satellite was in fact what it was believed to be and that it is still in operating condition. During or after the ASAT engagement with the target, the imaging system could verify that the satellite was visibly damaged, and aid in assessing the extent of the damage. With the current U.S. interest in curbing space debris[43] it is less likely the U.S. would consider an ASAT which broke the target into many, easily distinguishable pieces. Consequently, the ability to perform assessments of more subtle damage is required.

The worldwide proliferation of remote sensing satellites may provide the opportunity for any nation to obtain militarily significant satellite imagery. For example, the Soviets have reportedly sold photoreconnaissance photography to China.[44] As the economic situation in the former Soviet Union worsens, they may be more willing to sell satellite photography, if not the photoreconnaissance satellites themselves. General Kutyna, the Commander in Chief, U.S. Space Command, has been very specific in calling for a capability to meet this kind of threat:

---

[43] U.S. President, "U.S. Space Policy," (Washington, DC: The White House, Office of the Press Secretary, 16 November 1989).

[44] Nicholas L. Johnson, The Soviet Year in Space 1990 (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), p. 30-31.

> "Just as we would not tolerate enemy photoreconnaissance aircraft flying over our forces, we must not allow any enemy satellite to provide militarily useful data from space in wartime. Our forces obviously need a capability to counter this threat."[45]

Though not useful as a structural kill ASAT weapon,[46] even low power ground-based laser imaging systems may be useful as standby weapons for blinding space sensors.[47] In the 1986 edition of the DOD publication Soviet Military Power, it was suggested that the Soviets may already possess a satellite blinding capability.[48] It would seem, then, the U.S. military may want to possess a capability that any determined adversary may make an effort to obtain.

In the same article previously quoted, General Kutyna states that the U.S. Landsat, although a civilian remote sensing system, greatly assisted ground forces in Desert Storm.[49] The possibility that U.S. civilian satellites may be at risk in future conflicts helps make the case that such systems should be offered protection against hostile laser illumination themselves. Currently, however, there are no plans to implement laser protective measures on U.S. Landsat remote sensing[50] or civilian meteorological satellites.[51]

---

[45] General Donald J. Kutyna, "We Lead Today, But What About Tomorrow?" Defense 91, July/August 1991, p. 23 (based upon a prepared statement to the Senate Armed Services Committee, 23 April 1991).

[46] See discussion in chapter 4.

[47] As early as 1970, for example, it was reported that satellites could be "actively interrogated" to determine whether or not a satellite carries a down-looking optical sensor. Then, a more powerful laser could be introduced into the optical train to blind the satellite's sensor. See Barry Miller, "New Roles Grow for Electro-Optics," Aviation Week and Space Technology, 22 June 1970, p. 156.

[48] U.S. Dept. of Defense, Soviet Military Power (Washington, DC: GPO, 1986), p. 47.

[49] Kutyna, pp. 27, 29.

[50] Telephone conversation with John Hussey, Director, Landsat and Meteorological Satellite Development, National Oceanographic and Atmospheric Administration, 2 December 1991.

[51] Telephone conversation with William Peacock, Deputy Program Manager, Meteorological Satellites, NASA-Goddard Space Flight Center, 3 December 1991.

CIVIL APPLICATIONS OF GROUND-BASED LASERS IN SPACE

Civil applications of lasers in space are at least as broad as the potential military applications, as suggested in Figure 2. And, many of the applications listed as civil have significant military counterparts. Of most concern to the present study are those applications which, like the ground-based satellite imaging applications discussed above, transmit laser beams into space from the earth's surface. As such, they indicate possible directions for future civil laser technology development. The two which may have wide-spread applications in the civil sector are satellite laser ranging and laser guide stars for ground-based astronomy. Because lasers in these applications are not normally fired in the direction of DOD satellites, they represent an inadvertent laser illumination threat at worst.

Satellite Laser Ranging. Laser ranging techniques have been used since the early 1960's to range the moon and artificial satellites in earth orbit.[52] In 1962 researchers at the Massachusetts Institute of Technology's Lincoln Laboratory reported the first laser light echoes observed from the moon using a ruby laser.[53] Since that time, a number of optical retroreflector arrays has been left on the moon by the United States and the U.S.S.R., permitting detailed scientific study of the earth-moon system and tests of competing theories of general relativity.

The first laser range measurements to an artificial satellite carrying optical retroreflectors were made by NASA's Goddard Space Flight Center in 1964. They used a ruby laser, ranging the Beacon Explorer B satellite to a precision of a few meters. Today, satellite laser ranging (SLR) systems operated by NASA and elsewhere claim sub-centimeter ranging precision over

---

[52] Unless otherwise cited, the information in this section is drawn from John J. Degnan, "Satellite Laser Ranging: Current Status and Future Prospects," IEEE Transactions on Geoscience and Remote Sensing vol. GE-23, July 1985, pp. 398.

[53] L.D. Smullin and G. Fiocco, "Optical Echoes from the Moon," Nature vol. 194, 30 June 1962, p. 1267.

FIGURE 2

CIVIL APPLICATIONS OF LASERS IN SPACE

COMMUNICATIONS
- SATELLITE TO SATELLITE CROSSLINKS
- SATELLITE TO GROUND

ENVIRONMENTAL MONITORING
- WIND VELOCITY MEASUREMENTS
- ATMOSPHERE TEMPERATURE, WATER VAPOR, OZONE
- CLOUD HEIGHT

GEODESY
- CRUSTAL PLATE MOTION
- NAVIGATION SUPPORT

SPACE SENSOR CALIBRATION
- EARTH POSITION REFERENCING
- RADIANCE CALIBRATION

SATELLITE INSPECTION (IMAGING)
- TROUBLESHOOTING ON-ORBIT MALFUNCTIONS
- MONITORING SPACE STATION CONSTRUCTION

SPACE TRAFFIC CONTROL
- PRECISE RANGING FOR EPHEMIRIS
- SATELLITE IDENTIFICATION

GROUND-BASED ASTRONOMY
- LASER GUIDE STARS

POWER TRANSFER
- GROUND TO SPACE
- SPACE TO GROUND

LASER PROPULSION
- DEEP SPACE INJECTION
- DE-ORBITING SPACE DEBRIS

Source: Author.

satellite distances using ultra-short pulsed, frequency-doubled Nd:YAG lasers. As of 1985, approximately 14 satellites containing retroreflectors were put into orbit. By ranging such satellites from a number of ground stations, one can determine their relative positions of the sites providing accurate information for the study of the earth's mass distribution and tectonic plate motion. A typical satellite target is the Laser Geodynamics Satellite (launched in 1976), which is a heavy, 60 cm diameter metal sphere studded with 426 corner-cube retroreflectors, orbiting at an altitude of 5900 km. Range accuracies of 2-5 centimeters between ground stations "over continental distances" are reported . John Degnan of NASA-Goddard's Crustal Dynamics program suggests that satellite ranging of oceanographic satellites can also aid in the characterization of global sea state and ice topography.[54]

Currently, over 35 fixed satellite ranging stations are operating in over 20 counties and in every continent except Antarctica.[55] To support tectonic plate studies, NASA has developed a number of fully self-contained, mobile (MOBLAS) and transportable (TLRS) laser ranging stations. The mobile units (developed since 1969) are housed in trailer units while the transportable units, developed in the early 1980s, are contained in a small camper vans. Each mobile or transportable laser ranging station contains a ranging laser, beam directing (and receiving) telescope, instrumentation and support equipment. The ranging lasers used in the mobile NASA's SLRs, operating at 0.532 micrometers wavelength, produce 100 mJ of pulse energy in a 150 picosecond (10^{-12} sec) pulse width. The pulse repetition rate is typically 5 pulses per second. Because of the extremely short pulse length (needed to obtain high ranging precisions), the lasers exhibit peak pulse energies in excess of 600 megawatts; however, because of their low pulse repetition rate, the average emitted laser power is only one-half of a watt.

Currently, NASA's satellite laser ranging stations are sited in California, Western Australia, Mexico,and Maryland, while arrangements are being made to transfer mobile units to

---

[54] John J. Degnan, "Applications of Laser Ranging to Ocean, Ice, and Land Topography," <u>SPIE Proceedings</u> vol. 1492, 1991, p. 177.

[55] *Ibid.*

French Polynesia and Israel.[56] University operated satellite ranging stations connected with NASA's Crustal Dynamics Program operate at sites in Texas, Hawaii, and Peru. According to the laser trade press, mobile SLR stations are also either in use or under consideration by Italy, France, U.S.S.R, and China.[57] Pakistan are Rumania are reportedly considering installing fixed SLR ground stations. Figure 3 provides the locations of satellite laser ranging stations worldwide.

Laser Guide Stars for Ground-Based Astronomy. The use of laser guide stars was discussed above in the context of imaging satellites from the ground. For the same reasons that one would like to correct atmospheric turbulence for inspecting satellites, astronomers would like to improve the resolution and sensitivity of their ground-based astronomical telescopes. Because solid state detector technology is approaching the theoretical limits of optical detection sensitivity, further improvements in astronomical measurement sensitivity can only be made through the use of larger collecting telescopes (or, arrays of telescopes).[58] And, with the application of adaptive optics, the angular resolution of ground-based telescopes may approach their theoretical limits as well. Consequently, there is great current interest in fielding large ground-based telescopes with primary mirror collectors on the order of eight meters in diameter. According to Martin, et. al., "the 1990's should see a quadrupling of total light-collecting area available to astronomers."[59] See Table II.

---

[56] John J. Degnan, "An Overview of NASA SLR Stations and Their Performance," Seventh International Workshop on Laser Ranging Instrumentation, Matera, Italy, October 1989 (preprint).

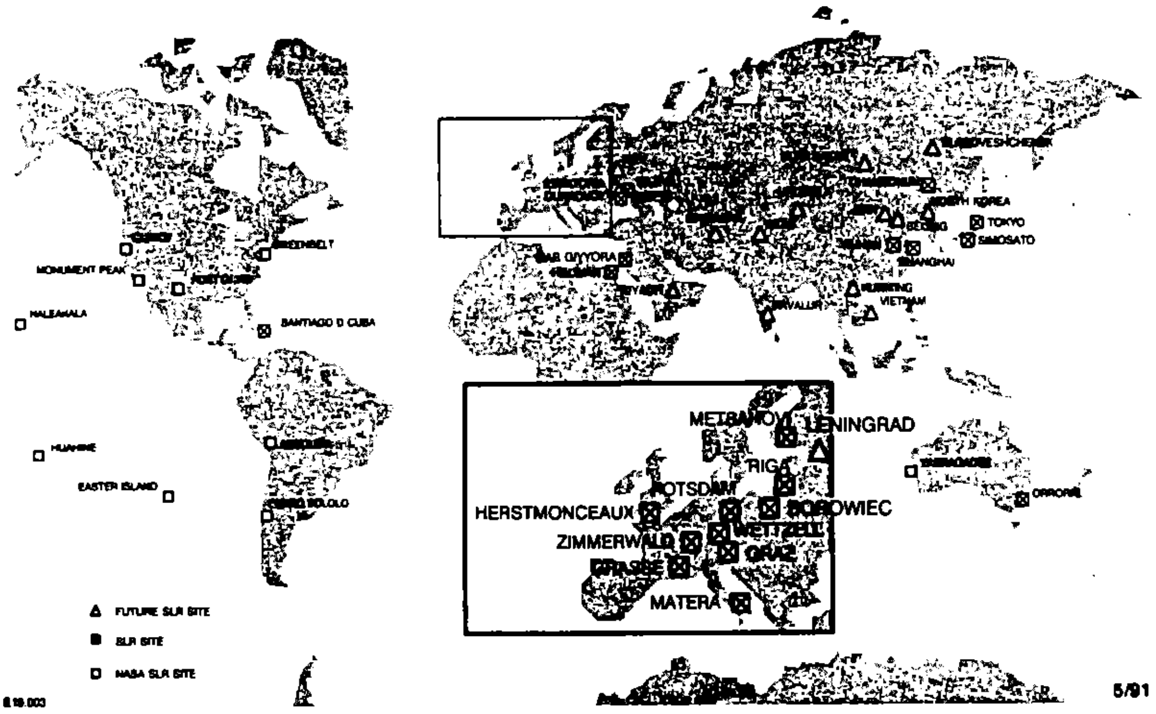
[57] Victor G. Lippay, "Laser Astronomy: An International Affair," Photonics Spectra, May 1989, p. 140.

[58] Buddy Martin, John M. Hill, and Roger Angel, "The New Ground-Based Optical Telescopes," Physics Today, March 1991, pp. 22-23.

[59] *Ibid.*, p. 23.

FIGURE 3

INTERNATIONAL SATELLITE LASER RANGING STATIONS



Source: J.J. Degnan, "Applications of Laser Ranging to Ocean, Ice, and Land Topography," SPIE Proceedings vol. 1492, 1991, p. 177.

TABLE II

MAJOR NEW GROUND-BASED ASTRONOMICAL TELESCOPES

PROJECT NAME	ORGANIZATIONS	TYPE/SIZE OF PRIMARY MIRROR
Very Large Telescope	European Southern Observatory	Four, 8.2-meter Telescopes
Columbus	Italy Ohio State University University of Arizona	Two, 8.4-meter Telescopes
Keck Telescope	Caltech University of California	10-meter Segmented
Magellan	Carnegie Institution Johns Hopkins University University of Arizona	8-meter
NOAO (North)	National Optical Astronomy Observatories Great Britain Canada	8-meter
NOAO (South)	National Optical Astronomy Observatories Great Britain Canada	8-meter
Japanese National Large Telescope	National Astronomy Observatory of Japan	7.5-meter
MMT Conversion	Smithsonian Institution University of Arizona	6.5-meter

Source: Buddy Martin, John M. Hill, and Roger Angel, "The New Ground-Based Optical Telescopes," Physics Today, March 1991, pp. 22-23.

The international astronomical community has been investigating laser guide star adaptive concepts since the mid-1980's. However, until this year it was not aware of classified work being conducted within the DOD.[60] Information recently released about DOD guide star tests demonstrates the viability of the adaptive optics concept, sparking great interest with astronomers.[61] According to Laird A. Thompson, an astronomer at the University of Illinois at Urbana who had reported the first sodium guide stars in the open literature,[62] "I think this technology will transform ground-based astronomy during the next ten or twenty years in ways you could hardly believe."[63] In addition to correcting single-aperture astronomical telescopes, he sees applications of laser guide stars to astronomical interferometers where arrays of telescopes may aid in the discovery of distant planetary systems.[64]

Already plans are being laid to incorporate laser guide star techniques on the world's largest telescopes. For instance, Edward Kibblewhite of the University of Chicago is reportedly constructing a sodium laser guide star system for use on the 3.5 meter Apache Point telescope in New Mexico.[65] Overseas, although formal plans to install laser guide star systems on their telescopes have not been drawn up, the European Southern Observatory has begun a development program. It is reported that prototype tests could be conducted on a 3.6 meter telescope at La Silla, Chile by 1995 with a follow-on implementation on one of the four

---

[60] Fugate, p. 144.

[61] Malcolm W. Browne, "Anti-Missile Technology Delights Astronomers," The New York Times, 6 August 1991, pp. C1, C9.

[62] Thompson and Gardner, p. 229.

[63] Browne, p. C9:1.

[64] *Ibid.*

[65] Graham Collins, p. 21.

planned 8.2 meter Very Large Telescope instruments at Cerro Paranal, also in the Chilean Andes.[66]

The cost of implementing laser guide star systems will be high by traditional astronomers' standards. Laird Thompson has estimated that a 241 actuator astronomical guide star adaptive optics system could be produced for $3.5 million.[67] Correcting an eight meter telescope will require hundreds to thousands of actuator channels, depending on the sensing wavelength and the extent of atmospheric turbulence at the site. Considering the cost of the large telescopes themselves (the cost of the 10 meter Keck telescope being installed at Mauna Kea, Hawaii is about $93 million), the additional cost of adaptive optics may, considering the potential improvement in resolution, be worth the price for the larger telescopes. If the actual performance of laser guide stars is shown to meet expectations, and if the cost to astronomers is not too great, it seems likely that this technology will find ever growing application in ground-based astronomy around the world.

Table III gives a comparison of recent guide star lasers developed for astronomy and geoscience applications. Besides their application to astronomy, sodium (laser) resonance studies of the upper atmosphere have been useful in studies of the earth's atmosphere and related physical processes. Such studies have been conducted at a half a dozen locations around the world, including Antarctica. Chester Gardner presents a recent, introductory review of these applications.[68]

---

[66] *Ibid.*

[67] *Ibid.*

[68] Gardner, pp. 408-418.

TABLE III

COMPARISON OF SELECTED RAYLEIGH AND SODIUM LIDARS

FACILITY	TYPE	LASER	WAVELENGTH (μM)	LASER POWER (W)
USAF Geophysics Laboratory, MA	Rayleigh	Nd:YAG	0.532	4
USAF Geophysics Laboratory, MA (portable)	Rayleigh	Excimer	0.351	16
Haute Provence, France	Rayleigh	Nd:YAG	0.532	4
CEDAR (Univ. of Illinois)	Rayleigh	Dye	0.589	5
Kyushu Univ., Japan	Rayleigh	Excimer	0.351	16
Syowa Station, Antarctica	Na	Dye	0.589	0.1
Sao Paulo, Brazil	Na	Dye	0.589	0.25
Andoya, Norway (Univ. of Bonn)	Na	Dye	0.589	0.3
Haute Provence, France	Na	Dye	0.589	0.6
Univ. of Illinois	Na	Dye	0.589	0.4
CEDAR (Univ. of Illinois)	Na	Dye	0.589	5

Source: C.S. Gardner, "Sodium Resonance Fluorescence Lidar Applications in Atmospheric Science and Astronomy," Proceedings of the IEEE 77, p. 408 (1989).

CHAPTER III

LASER ILLUMINATION POLICY ENVIRONMENT

ASPECTS OF INTERNATIONAL SPACE LAW

While no specific treaty provision or point of international space law specifically prohibits laser illumination of satellites for any reason, the effect that such illumination may have on the spacecraft touches on a number of fundamental issues. These issues are important for laser illumination policy because they establish the desired norm of international behavior in space. Since the U.S. will not enter into any international agreement it judges not to be in its national interest, it is generally U.S. policy to adhere to the terms of agreements to which it is a party.

PROTECTION OF SOVEREIGN RIGHTS

The Outer Space Treaty (OST) of 1967, colloquially known as the "Magna Carta of Space," establishes the basic rights and responsibilities of space faring nations in the exploration and use of outer space.[1] It establishes that outer space is for the use by all States, "without discrimination of any kind, on a basis of equality and in accordance with international law."[2]

Space activities will be conducted in accordance with international law, which includes the Charter of the United Nations.[3] The fact that Article 51 of the U.N. Charter provides for the "inherent right for individual or collective self-defense" implies that there is no prohibition

---

[1] Full title of the treaty is "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies." See, for example, Carl Q. Christol, The Modern International Law of Outer Space (New York: Pergamon Press, 1982), pp. 851-857, for text of agreement.

[2] Outer Space Treaty, Article I; see Christol, p. 852.

[3] *Ibid.*, Article III.

on defensive systems operating in space. The much debated Article IV of the OST,[4] however, prohibits the deployment of any objects carrying nuclear weapons or any other kinds of weapons of mass destruction. While specifically prohibiting these weapons and the testing of weapons on celestial bodies, all other weapons not specifically banned (e.g., antisatellite weapons in orbit about the earth) are permitted. The 1979 Moon Treaty extends the prohibition on military activities to all celestial bodies in the solar system except earth.[5] Military activities in earth orbit are therefore still permitted.

Articles VI and VII of the Outer Space Treaty pertain to the responsibility and liability, respectively, of states for their actions or the actions of non-governmental entities within their jurisdiction. State Parties to the Treaty bear international responsibility for their activities in space, and must assure that such activities conform to the provisions of the Treaty. Similarly, State Parties are internationally liable for damage to another State Party or its persons on earth, in the air, or in space through its activities in space. The 1971 Convention on International Liability[6] expands on the meaning of liability, stating that the launching state is absolutely liable for damage done to objects or people on earth or in the air. When the object damaged is in space, however, the launching state is liable only when the damage is due to its fault or the fault of its responsible personnel. This distinction suggests that launching nations are always responsible for damage caused when a satellite reenters the earth's atmosphere and impacts on the surface, but is not if the satellite collides with another by accident. Applying this concept to the possible accidental laser illumination of satellites from the ground suggests that parties firing laser beams into space would be liable for damage if the event could have been avoided.

---

[4] Christol, pp. 30-35.

[5] Curtis D. Cochran, et al., Space Handbook (Maxwell AFB, AL: Air University, 1985), p. 15-3.

[6] "Convention on International Liability for Damage Caused by Space Objects," signed June 29, 1971; see Christol.

Article VIII states that objects launched into space or on a celestial body are retained under the jurisdiction of the State on whose registry the object was launched.[7] This means that such objects are the national property of the launching state throughout their flight through space (and, even after they have returned to earth) and are, for legal purposes, part of that country's national territory. Any action, including laser illumination, which is considered to be damaging or interfering would violate sovereign rights of the state in which the satellite is registered.

Article IX addresses, but does not resolve, the issue of harmful interference. According to this article, states shall "be guided by the principle of cooperation and mutual assistance and shall conduct all their activities in outer space ... with due regard to the corresponding interests of all other States Parties to the Treaty."[8] This implies that, subject to exceptions provided under the right to self-defense, nations shall conduct their activities in space so as not to interfere with the normal and rightful operation of another nation's satellite. The article does not, however, specify what is meant by the term, "interference." It states

> "If a State Party to the Treaty has reason to believe that an activity or experiment planned by it or its nationals in outer space, including the moon and other celestial bodies, would cause potentially harmful interference with activities of other States Parties in the peaceful exploration and use of outer space, including the moon and other celestial bodies, it shall undertake appropriate international consultations before proceeding with any such activity or experiment. A State Party to the Treaty which has reason to believe that an activity or experiment planned by another State Party ... would cause potentially harmful interference with activities in the peaceful exploration and use of outer space ... may request consultation concerning the activity or experiment.[9]

---

[7] See also Articles II and IV of the Registration Convention (1975); see Christol.

[8] Outer Space Treaty, Article IX; Christol, pp. 854-855.

[9] *Ibid.*

Evidently, the burden of proving what is harmful does not lie entirely with either party, but rather, should be worked out cooperatively in "consultation." Since it may be difficult to ascertain conditions under which a foreign satellite may be harmed by laser illumination (especially, those with sensitive, earth-viewing optical systems), it may be necessary to seek consent of the state owning the satellite. Article IX of the Outer Space Treaty provides for that dialogue.

Article X of the Outer Space Treaty, however, reserves the right of party states to "observe the flight of space objects." According to Christol[10] the original intent of this article was to give signatories the opportunity to observe foreign space launches. While national sovereignty does not extend into outer space, there would seem to be adequate legal precedent for establishing the right to observe satellites in orbit, given the thirty-five year history of tracking satellites from the earth with radar and passive optical sensors (telescopes). So long as the observation sensors do not interfere with the normal operation of the observed spacecraft, then, the article suggests that states have the right to observe satellites in orbit. This position would be supported, for example, by any nation interested in protecting their terrestrial sovereignty from the prying eyes of remote sensing satellites overflying its homeland. Their self-interest in preserving territorial sovereignty or an advantageous economic bargaining position with respect to their natural resources might, under sufficient provocation, cause them to take up a defense against such overflights.[11]

Taken together, the OST implies that satellites of party nations have the "right of passage" through space, similar to that which ships have on the open sea. Consequently,

---

[10] Christol, p. 49.

[11] For an introduction to the political and legal issues implications of remote sensing, see David S. Simonette, "The Development and Principles of Remote Sensing," Robert N. Colwell, ed., Manual of Remote Sensing, vol. I, chap. 1(Falls Church, VA: American Society of Photogrammetry, 1983), pp. 16-19 and the references therein.

unprovoked interference with the normal operation of space ships could be viewed as a hostile act. President Bush recognizes these concepts and accepts them as a part of U.S. Space Policy:

> "The U.S. considers space systems of any nation to be national property with the right of passage through and operations in space without interference. Purposeful interference with space systems shall be viewed as an infringement on sovereign rights."[12]

Again, however, the meaning of the term interference is left to interpretation.

It has been suggested that interference does not require actual contact with the spacecraft.[13] For example, if a spacecraft is placed in close orbital proximity to another for the purposes of inspection, a perceived risk of collision may be perceived as interference.[14] On the other hand, extremely low levels of laser radiation may not even be detectable except by sensitive optical detectors, unless the sensor was looking back into the laser beam and tuned to the laser's wavelength.[15] Thus, illumination by low power lasers could be judged not to be a threat, unless it was believed that laser illumination was performed with harmful intent (e.g., sensor blinding or weapons targeting).

INTERFERENCE WITH NATIONAL TECHNICAL MEANS

The development of advanced sensor technologies which could remotely gather information about Soviet terrestrial military activities (and, conversely, Soviet capabilities to

---

[12] U.S. President, "U.S. Space Policy," (Washington, DC: The White House, Office of the Press Secretary, 16 November 1989).

[13] Paul B. Stares, "Rules of the Road for Space Operations," Barry M. Blechman, ed., Technology and Limitation of International Conflict (Washington, DC: Johns Hopkins University), p. 102.

[14] Memorandum from U.S. Air Force Space Command (JA) to U.S. Air Force Space Command (IN), "Space Treaty Questions," 24 July 1989.

[15] See Chapter 4 for an extensive discussion of this point.

monitor U.S. military activities) greatly facilitated the development of an arms control regime for the limitation of Strategic Nuclear Arms--beginning with the ABM Treaty and Interim Agreement on Strategic Offensive Forces Agreement of 1972. These technical measures, which are generically referred to as "national technical means" (NTM), give reassurance that provisions of these accords are being complied with. The U.S. State Department has formally defined NTM as "Assets under national control for monitoring compliance with the provisions of an agreement."[16] Further, since these sensors collect information from locations external to the country being monitored (e.g., from the periphery of the Soviet Union or from space), they are less intrusive and therefore more acceptable to party states than on-site inspection or other intrusive measures. It is widely acknowledged that the development of these sophisticated technical capabilities, especially photoreconnaissance satellites, were the "breakthrough" which in fact made agreements on strategic arms control possible.[17] Adequate verification by NTM has been made a precondition for all subsequent U.S. agreements on strategic offensive arms.[18]

As capable as the NTM had become, however, these systems could not support the treaty verification process unaided.[19] Control clauses had to be added to these agreements prohibiting interference with, and ensuring transparency for, the operation of NTM. Article XII of the ABM Treaty states

---

[16] William F. Rowell, Arms Control Verification: A Guide to Policy Issues for the 1980s (Cambridge, MA: Ballinger, 1986), p. 51 citing U.S. Department of State, Bureau of Public Affairs, Security and Arms Control: The Search for a More Stable Peace (Washington, DC: U.S. Dept. of State, 1983), p. 65.

[17] Christol, p. 31.

[18] U.S. Congress, Senate, Department of Defense Appropriations for Fiscal 1975,"Basic Principles of Negotiations on Future Limitation of Strategic Offensive Weapons," (Washington, DC: GPO, 1975), p. 61, para. 4.

[19] Coit D. Blacker and Gloria Duffy, International Arms Control: Issues and Agreements, Second Edition (Stanford, CA: Stanford University Press, 1984), p. 253.

> "Each Party undertakes not to interfere with the national technical means of verification of the other Party ... [and] not to use deliberate concealment measures which impede verification by national technical means of compliance with the provisions of this Treaty."[20]

Similar statements are contained in the SALT I Interim Agreement and in every strategic nuclear arms control accord since 1972.[21] Interference with space-based NTM may include any number of measures including electronic jamming or "spoofing," interference with satellite's communications with its ground stations, or physical attack.[22]

Using ground-based lasers to intentionally blind or "dazzle" optical systems on satellites might violate Article XII of the ABM Treaty, either in terms of the requirement not to "interfere with" NTM or the requirement not to use "deliberate concealment measures" to impede verification.[23] In 1978 Cyrus Vance testified that the "Soviet use of lasers to blind certain U.S. satellites could be an activity inconsistent with obligations in Article XII of the ABM Treaty and Article V of the Interim Agreement" on both these counts.[24] Correspondingly, it is in the U.S. interest to avoid appearing to interfere with Soviet space NTM systems. During the negotiation period leading up to the 1972 SALT agreements the Director of Defense Research and Engineering, John S. Foster, Jr., issued a directive imposing

---

[20] ABM Treaty, Article XII; for text of treaty see, for example, Roger P. Labrie, ed., Salt Hand Book: Key Documents and Issues 1972-1979 (Washington, DC: American Enterprise Institute for Public Policy Research, 1979), pp. 18.

[21] John M. Collins, Military Space Forces: The Next 50 Years, Congressional Research Service Report 89-578 RCO (Washington, DC: The Library of Congress, 12 October 1991), p. 42.

[22] Robert B. Giffen, U.S. Space System Survivability:Strategic Alternatives for the 1990s, National Security Affairs Monograph 82-4 (Washington, DC: National Defense University Press, 1982), p. 26.

[23] See quote above.

[24] Labrie, pp. 535-6. In the same testimony, Cyrus Vance stated that alleged Soviet blinding of U.S. launch detection satellites reported by the press in 1975 had been determined to be caused by several large gas pipeline fires. See Philip J. Klass, "Anti-Satellite Laser Use Suspected," Aviation Week and Space Technology, 8 December 1975, pp. 12-13.

strict controls on the emission of laser beams from DOD laser test facilities.[25] The purpose of this directive was to prevent inadvertent laser illumination of Soviet space systems by U.S. military lasers and, presumably, to strengthen confidence on this point by avoiding the appearance of interfering with Soviet NTM.

The importance of NTM for verifying treaty verification was at its peak during the cold war. During the latter part of the 1960s and 1970s, the capabilities of the NTM were such that Soviet ICBM tests and operational deployments could be monitored for conformity with the terms of the negotiated accords. As the SALT I agreements (including the ABM Treaty) could not have been achieved without adequate NTM, any threat to these systems might be perceived as a concomitant threat to strategic arms control itself. As Scoville and Tsipis have suggested, interference with photoreconnaissance satellites "would not only contravene agreements like the ABM Treaty but could immediately halt any restraint on weapons procurement ... the provocation would be so strong as to be considered an act of war."[26]

Under conditions which have been referred to as an "accident of technology," however, it has been suggested that the SALT I arms control agreements were only possible at a time when the capabilities of verification technology effectively matched the offensive weapons technology of the time.[27] The increased level of technical sophistication of strategic weapons and consequent requirements of later arms control agreements[28] have led increasingly to the

---

[25] Memorandum for Secretary of the Army, Secretary of the Navy, Secretary of the Air Force, and Director, Advanced Research Projects Agency, "Irradiation of Aircraft and Satellites by Lasers," Director of Defense Research and Engineering, 24 July 1970. FOR OFFICIAL USE ONLY Hereafter referred to as the "Foster Memorandum."

[26] Christol, p. 31.

[27] Rowell, p. 47.

[28] See, for example, provisions for "functionally related observable differences" in the negotiated but unratified SALT II Treaty. Blacker and Duffy, pp. 446-469.

use of on-site inspections and other more invasive measures.[29] The ascendence of low-observable technology (e.g., cruise missiles and land-mobile missiles) has meant that, as Rowell states, "an increasingly larger number percentage of capable weapons systems can no longer be confidently monitored by unaided national technical means of verification."[30] As early as 1981, the then-current director of U.S. Arms Control and Disarmament Agency, Eugene Rostow, recognized

> "We are approaching the limit, if we have not passed it, in many areas of what can be verified reliably by NTM. NTM simply are not adequate to verify missile production, for example, or the number of warheads actually on missiles. There are many things that are simply beyond the reach of our NTM no matter how sophisticated they are, and they are very sophisticated.[31]

These and other limitations in the potential use of NTM for monitoring strategic weapons accords, however, do not diminish the utility of these platforms for other missions (science, military force enhancement, etc.),[32] but these missions are not specifically protected by international law except in the context of self-defense. Also, owing to reduced tensions between the U.S. and the former Soviet states, the actual CIS response to a suspected laser illumination event would not likely be as severe as that feared during the height of the Cold War.

CONFIDENCE BUILDING MEASURES

Confidence building measures are agreements which seek to constrain military activities and provide communications improvements in order to reduce the risk of inadvertent war or

---

[29] Rowell, pp. 47-51.

[30] Rowell, p. 150.

[31] Rowell, p. 50.

[32] See, for example, Rowell, pp. 24-30 for a discussion of the relation between NTM and intelligence.

surprise attack.[33] Laser illumination of certain satellites may violate either the letter or spirit of a number of other bilateral accords designed to reduce the risk of nuclear war. The 1963 and 1971 U.S.-U.S.S.R "Hotline" agreements[34] established, and then upgraded with satellite communications circuits, a direct communications link between the leadership of the two superpowers. These agreements were designed to allow the Parties to clarify their intentions in cases of accident, miscalculation, or misunderstanding and thus avert an unintended war. Article II of the 1971 Hot Line agreement requires the signatories to "take all possible measures to assure continuous and reliable operations of the communications circuits and the system terminals of the direct communications link." Hence, interference with the Intelsat (U.S.) or Molniya (U.S.S.R.) communications satellites or their ground stations would violate the provisions of these accords.

Following on the Hot Line agreements, the 1971 "Accidental Measures" agreement[35] requires the U.S. and U.S.S.R. to notify each other in the event of "detection of missile warning systems of unidentified objects, or in the event of signs of interference with these systems or with related communications facilities." The 1973 Prevention of Nuclear War agreement[36] calls on the U.S. and U.S.S.R. to "act in a manner as to prevent the development of situations capable of causing dangerous exacerbation of their relations, so as to avoid military confrontations, and to exclude the outbreak of nuclear war." Thus, through these

---

[33] Sean M. Lynn-Jones, "A Quiet Success for Arms Control," International Security, Vol. 9, Spring 1985, p. 154.

[34] Full titles of these agreements are the "Memorandum of Understanding Between the United States of America and the Union of Soviet Socialist Republics Regarding the Establishment of a Direct Communications Link" (1963) and the "Agreement Between the United States of America and the Union of Soviet Socialist Republics on Measures to Improve the U.S.A.-U.S.S.R. Direct Communications Link" (1971), respectively. See Blacker and Duffy, pp. 117-119 for complete texts.

[35] "Agreement on Measures to Reduce the Risk of Outbreak of Nuclear War Between the United States of America and the Union of Soviet Socialist Republics," see Blacker and Duffy, pp. 406-7 for text.

[36] "U.S.-U.S.S.R. Agreement on Prevention of Nuclear War," 22 June 1973.

agreements the U.S. and Soviet Union agree to avoid provocative actions, such as illuminating each other's launch detection satellites, and to contact each other if such an event accidentally occurred or is believed to have occurred.

In 1989, the U.S. and Soviets signed the Dangerous Military Activities Agreement (DMA)[37] which seeks to restrain dangerous peacetime military (generally non-nuclear) activities and improve communications between their armed forces when operating in close proximity to each other. While perhaps useful as a model of future agreements pertaining to military activities in space, this agreement focuses on terrestrial (land, sea, and air) military exercises and activities only--space systems are not mentioned and satellites are specifically excluded from the definition of "aircraft."

SUMMARY

Table IV summarizes the restrictions on laser illumination implied by the in-place bilateral and multi-lateral agreements discussed in this section.

---

[37] U.S. Treaties, etc. "Agreement Between the Government of the United States of America and the Government of the Union of Soviet Socialist Republics on the Prevention of Dangerous Military Activities," signed 12 June 1989.

TABLE IV

PROVISIONS OF INTERNATIONAL LAW PERTAINING TO LASER ILLUMINATION OF SATELLITES

ISSUE CLASS	TREATY	SCOPE	APPLICATION	QUESTIONS PERTAINING TO SATELLITE ILLUMINATION
SOVEREIGN RIGHTS	OUTER SPACE TREATY (1967), ART. IX	MULTILATERAL	"HARMFUL INTERFERENCE" WITH SATELLITES OF ALL PARTY STATES	WHAT IS HARMFUL INTERFERENCE?
NATIONAL TECHNICAL MEANS (NTM) OF VERIFICATION	ABM (1972), ART. XII THRESHOLD TEST BAN (1974), ART II	BILATERAL (U.S.-U.S.S.R)	INTERFERENCE WITH NTM SATELLITES	WHAT SATELLITES ARE NTM? WHAT CONSTITUTES INTERFERENCE TO NTM SATELLITES?
CONFIDENCE BUILDING (NUCLEAR WAR)	HOT LINE AGREEMENT (1971)	BILATERAL (U.S.-U.S.S.R)	INTERFERENCE WITH DIRECT COMMUNICATIONS LINK (DCL) SATELLITES	WHAT CONSTITUTES INTERFERENCE TO DCL SATELLITES?
	PREVENTION OF NUCLEAR WAR AGREEMENT (1973)	BILATERAL (U.S.-U.S.S.R)	PROVOCATIVE ACTIONS	WHAT ACTIONS AGAINST SATELLITES ARE CONSIDERED PROVOCATIVE?
CONFIDENCE BUILDING (CONV. WAR)	DANGEROUS MILITARY ACTIVITES (1989)	BILATERAL (U.S.-U.S.S.R)	MILITARY OPS ON EARTH	N/A

U.S. SPACE POLICY GUIDANCE

The U. S. national goals in space are articulated in the President's National Space Policy statement, the latest issuance appearing in November 1989.[38] This statement establishes national policy, guidelines, and implementing actions for the conduct of the civil, national security, and non-governmental commercial sectors of the U.S. space program. These goals may be summarized as

- Strengthen the security of the United States,
- Obtain scientific, technological, and economic benefits for the general population and enhance the quality of life on earth,
- Encourage continued U.S. private sector investment in space,
- Promote international cooperative activities taking into account U.S. national security, foreign policy, scientific, and economic interests,
- Cooperate with other nations in maintaining the freedom of space for all activities that enhance the security and welfare of mankind, and
- As a long-range goal, expand human presence and activity into the solar system.

As suggested by its precedence in the list above, the President's commitment to national security is paramount. While affirming its support to the use of space for peaceful purposes, the policy clearly states that "peaceful purposes" include the pursuit of national security goals. The U.S. will conduct activities in space in support of its "inherent right of self-defense and its defense commitments to its allies." Further, the Space Policy endorses the concepts of international space law stating that space systems of any nation are national property with the right of passage through space without interference.

---

[38] U.S. President, "U.S. National Space Policy," (Washington, D.C.: The White House, Office of the Press Secretary, 16 November 1989).

The U.S. Space Policy specifically identifies those activities which are necessary for national defense, points which are delineated in the U.S. Military Space Policy[39] announced two and one-half years earlier:

> "Space activities will contribute to national security objectives by (1) deterring, or, if necessary, defending against enemy attack; (2) assuring that forces of hostile nations cannot prevent our use of space; (3) negating, if necessary, hostile space systems; and (4) enhancing operations of U. S. and allied forces. Consistent with treaty obligations, the national security space program shall support such functions as command and control, communications, navigation, environmental monitoring, warning, surveillance , and force application (including research and development programs which support these functions)."[40]

The U.S. and DOD Space Policies, then, openly proclaim the right to for the U.S. to conduct a wide range of military activities in space consistent with its treaty obligations (as discussed in the previous section). By comparison, the former Soviet Union had not until 1985 recognized the rights of nations to conduct military activities in space.[41] Its definition for "peaceful purposes" had been interpreted to mean strictly non-military activities which is distinct from the traditional U.S. interpretation of peaceful purposes which implies non-aggressive activities. The U.S. interpretation appears to be consistent with the generally held international position that the military use of space is permitted by international law.[42] In short, U.S. military space activities support the national security objectives by helping to deter conflict during peacetime. But, if deterrence fails, military space forces may be employed to support U.S. and allied

---

[39] U.S. Dept. of Defense, "Department of Defense Space Policy," Memorandum for Correspondents, March 10, 1987.

[40] "U.S. National Space Policy," 16 November 1989.

[41] Nicholas L. Johnson, The Soviet Year in Space 1990 (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), p. 81.

[42] Marietta Benko, et al., Space Law in the United Nations (Boston: Martinus Nijhoff Publishers, 1985), p. 176.

forces on earth, to ensure U.S. access to space and, if necessary, to defend against enemy attack or destroy hostile space systems. To the extent that laser illumination supports these goals and are consistent with international law, one would expect such activity to conform to the stated U.S. space policy.

By acknowledging the U.S. right to conduct military research and development in space (again, subject to limits imposed by treaty obligations), the policy preserves U.S. freedom of action as new technology may be applied in the future. Also, it preserves freedom of action by reserving for the U.S. the right to formulate new policy positions on arms control measures governing activities in space, stating that it will conclude these agreements only if "they are equitable, effectively verifiable, and enhance the security of the U.S. and our allies."

U.S. POLICY TOWARD ANTISATELLITE WEAPONS

While wishing to maintain broad freedom of action in its military space activities, the Bush administration has made no specific policy stand regarding the laser illumination of foreign satellites. The use of lasers against objects in space does, however, touches on a number of important policy issues pertaining to the development and use of antisatellite weapons.

The development of weapons to kill satellites has been a part of the U.S. and Soviet military programs since the late 1950s.[43] Although the Carter Administration had attempted to negotiate a bilateral curb on antisatellite weapons with the Soviets in the late 1970s, the Reagan and Bush administrations have not seen it in the U.S. interest to place a ban on either ASAT weapons or their development. This latter position has been justified by analysis which shows that an ASAT ban is not verifiable and because the consequences of even a limited Soviet

---

[43] Paul B. Stares, The Militarization of Space: U.S. Policy, 1945-1984 (Ithaca, NY: Cornell University Press, 1984), pp. 106-235.

breakout from such a treaty ban might be considered too risky.[44] Furthermore, opposition to an ASAT ban supports the desire to preserve U.S. freedom of action in the development and possible deployment of more advanced weapons technology. The SDIO, for example, had reportedly planned to test its space-based Alpha laser as an ASAT in order to exploit a loophole in the ABM Treaty which permits the testing ABM components so long as they are not tested in an "ABM mode".[45]

The U.S. Congress has not not entirely supported the administration's claims that the U.S. needs an ASAT weapon. Although approving funding for the development of the Air Force's Miniature Vehicle (MV) ASAT during the 1980's, restrictions were placed on its testing against objects in space.[46] More recently, while appropriating a total of $193 million for ASAT research and development in FY1991, the DOD authorization bill prohibited testing of one specific laser system, the U.S. Army's Mid-Infrared Advanced Chemical Laser (MIRACL), against objects in space unless specifically authorized by Congress.[47] The FY1992 authorization act extends the space testing prohibition on MIRACL through fiscal year 1992.[48]

How does all this relate to the issue of laser illumination? Again, although the Bush administration has not issued a stand on laser illumination of foreign satellites, per se, the

---

[44] Marcia S. Smith, "ASATs: Antisatellite Weapons Systems," Congressional Research Service Issue Brief, Order Code IB85176 (Washington, DC: The Library of Congress, 11 December 1991), p. 11 .

[45] Eric H. Arnett, "Antisatellite Weapons Issue Paper," AAAS Program on Science, Arms Control, and National Security, AAAS Publication No. 90-11S (January 1990), p. 10.

[46] M.S. Smith, pp. 12-13. The Tsongas amendment to the FY1984 authorization act prohibited tests of the MV in space unless the President certified that progress was being made in ASAT negotiations with the Soviets and the tests were necessary.

[47] *Ibid.*

[48] U.S. Congress, House, Conference Report to Accompany H.R. 2100, National Defense Authorization Act for Fiscal Years 1992 and 1993, Report 102-311 (Washington, DC: GPO, November 13, 1991), p. 28.

policy would presumably support laser illumination so long as (1) it supported national security interests, (2) it did not violate the intent of international law, and (3) it did not jeopardize other more significant national security developments. One might find enthusiastic support if the laser illumination issue could actually facilitate a favorable resolution of such issues with Congress. The congressional position toward MIRACL testing suggests that Congress believes MIRACL crosses some kind of "ASAT weapons threshold," even though it is doubtful the device represents a viable weapon system. Perhaps Congress' perception of what delineates an ASAT threat can be used in framing a workable regime for laser illumination of satellites at lower power levels.

CURRENT U.S. CONTROLS ON SATELLITE ILLUMINATION

Although, no coordinated U.S. policy specifically addressing the laser illumination of foreign satellites currently exists, the Department of Defense operates an informal, yet effective, set of procedures for controlling the emission of laser energy into space under the USSPACECOM Laser Clearinghouse (LCH).[49]

THE SPADOC LASER CLEARINGHOUSE

Within the DOD, the Commander in Chief, United States Space Command (USCINCSPACE) is the central point of contact for authorizing the emission of laser radiation into space which has the potential of interfering with or damaging U.S. or foreign satellite payloads.[50] USCINCSPACE accomplishes this task through the Space Defense Operations

---

[49] The Joint Chiefs of Staff have recommended that the controls and procedures followed by the Laser Clearinghouse be formalized. A policy statement for the prevention of inadvertent damage to satellites is contained in a proposed DOD Directive. Memorandum for the Secretary of Defense, "DOD Directive on Preventing and Reporting Accidental and Damaging Illuminations of Satellites by Laser Systems," JCSM-169-87, 29 September 1987. See further discussion below.

[50] U.S. Department of Defense, U.S. Space Command, Space Defence Operations Center Laser Clearinghouse, USSPACECOM Pamphlet XXX-XX (DRAFT) (Peterson AFB, CO: 1 January 1988), pp. 1-2.

Center (SPADOC) at Cheyenne Mountain Air Force Base, CO which, among other things, operates the Laser Clearinghouse program. The purpose of this program is to assist DOD laser operators and U.S. satellite owner/operators in preventing laser light from accidentally harming U.S. or foreign satellites. Establishing guidelines and operating procedures for the SPADOC Laser Clearinghouse are provided in the draft USSPACECOM Pamphlet XXX-XX.[51] These guidelines apply to all DOD laser facilities whether fixed or mobile, whether on land, on sea, in the air, or in space. DOD lasers, according to the USSPACECOM Pamphlet, are those "owned, operated, or controlled by DOD components or by agencies or contractors under the auspices of DOD components." The LCH responsibilities are to (1) evaluate the damage potential of DOD lasers, (2) schedule laser emission from DOD sources to avoid interference or damage to U.S. or foreign satellite payloads, and (3) respond in analyzing accidental laser illumination events. The procedures by which the LCH fulfills the first two responsibilities are discussed below.

The process of regulating laser emissions begins when the LCH requests operating data (laser type, wavelength, peak power, beam divergence, pulse length, etc.) on DOD laser systems from the system operators. Currently, the LCH has compiled such data on several hundred laser devices at over one hundred laser site locations.[52] Based on this data for each device, the LCH determines whether, if fired into space, the laser radiation would be a threat to a satellite. This threat assessment is performed by comparing a computed laser operating intensity (determined by the laser's operating time and its peak emitted brightness) against a

---

[51] *Ibid.*, pp. 1-25.

[52] Telephone conversation with Lieutenant James Thilenius, USN, U.S. Space Command, Space Control Operations Technical Support Branch (J3SOT), Peterson AFB, CO, 18 February 1992.

standard damage threshold curve.[53] If the laser's operating intensity exceeds the damage threshold standard, the laser is judged to have the potential to damage satellite payloads.

Based on this threat assessment, the LCH applies one of three waiver classes for ground-based lasers which could be radiated into space:[54]

(1) Blanket Waiver -- the laser poses no threat to space systems,

(2) Conditionally Waiver -- the laser is a threat only when fired above some elevation angle (above the horizon) determined by the LCH, or,

(3) "Non-waived" -- the laser is determined to have the potential of interfering or damaging space systems when fired into space. The damage threshold standard used in the threat assessment is believed to be conservative in order to be certain of protecting satellite optical payloads, but not overly so. The cited minimum threshold brightness value is 66.7 gigawatts[55] per steradian, corresponding to a minimum radiated laser power of about 5 watts.[56] Thus, any laser transmitting a peak power less than 5 watts should fall into the waived category, but lasers transmitting considerably more power may be waived because of their large beam divergence angles (transmitted beam divergences of tens to hundreds of

---

[53] USSPACECOM Pamphlet XXX-XX, Attachment 2, "Laser Damage Threshold Comparison Procedures," pp. 10-11.

[54] Though not directly pertinent to the present discussion, the LCH also has three other "special waivers" which apply to lasers which are (1) totally enclosed in a building, (2) fired toward the earth (say, from the ground or from an aircraft), or (3) supporting operational satellite communications crosslinks. USSPACECOM Pamphlet XXX-XX, p.3.

[55] One gigawatt is equal to 10^9 watts.

[56] The equation relating laser brightness to radiated power is given by $B = P/\Omega$, where B is the brightness, P the laser's total radiated power, and Ω is the solid-angle beam divergence. The solid-angle beam divergence Ω is related to the half-angle beam divergence θ by $\Omega = \pi\theta^2$. A laser with a brightness of 66.7×10^9 watt/sr projecting into a 5.0 microradian half-angle beam, then, corresponds to a laser system radiating 5.24 watts. Five microradians is the approximate diffraction-limited (half-angle) beam divergence for a laser transmitted from the ground vertically through the atmosphere.

microradians are not uncommon at visible wavelengths). The vast majority of lasers registered with the LCH are categorized as blanket-waived.

Laser facilities operating conditionally waived or non-waived lasers must request permission from the SPADOC whenever such lasers are radiated into space. When the operator wishes to fire such a device into space, he may ask the LCH to provide safe firing windows based on the intended laser firing direction and the known positions of satellites. These "predictive avoidance" windows give laser start and stop times so that no active satellite will be illuminated. In computing predictive avoidance windows, the LCH normally assumes any active satellite (without regard to its mission or laser vulnerability) would be harmed if illuminated by a non-waived laser and so avoids such contact. The choice to assume all active payloads may be interfered or damaged by laser illumination is largely a practical one since vulnerability data on all spacecraft (U.S. and foreign) may not be available.

When the laser operator wishes to conduct a test in which a satellite is to be illuminated with a laser intentionally, it is the responsibility of the laser operator to obtain permission from the owner/operator of the intended target satellite.[57] This rule applies to all satellites and to all lasers independent of the LCH waiver class. Thus, even blanket-waived lasers which are judged to have "no potential of interference or damage to space systems" for predictive avoidance purposes, may not be fired in the direction of any satellite without permission. The permission rule applies to all U.S. satellites--with the single exception of U.S. satellites containing laser reflectors and designed to be laser illuminated--and, as previously stated, to all foreign satellites as well.

---

[57] USSPACECOM Pamphlet XXX-XX, Paragraph 5.c.(5), p. 6.

"NOT ONE PHOTON"

The permission rule originated in a July 1970 directive issued by Director of Defense Research and Engineering, Dr. John S. Foster, Jr.[58] At the time it was felt that unrestricted use of DOD lasers against Soviet satellites might be perceived as interfering with their national technical means of verifying provisions of the treaties resulting from the SALT I talks (c.f., earlier discussion on the SALT I ABM Treaty and Interim Agreement of 1972). Similarly, the U.S. did not want to invite an in-kind Soviet response which would interfere with its NTM assets. In seeking positive controls on DOD laser emissions directed toward satellites (and aircraft), the Foster Memorandum requires that

> "any experimental, test, or operational activity utilizing a laser device for the purpose of irradiating any target aircraft or satellite will, in advance of such action, (a) secure the consent and approval of the organization responsible for the operational safety of such target aircraft or spacecraft; or (b) determine that such irradiation will not exceed maximum safe exposure levels prescribed by the Director of Defense Research and Engineering; or (c) be authorized by a project or program plan (e.g., communications, surveillance, and similar applications) reviewed by the Director of Defense Research and Engineering."[59]

The effect of the Foster Memorandum is to impose tight restrictions on the illumination of foreign satellites. Because definitive damage criteria could not be established without Soviet cooperation, and because the sites did not individually seek permission to illuminate Soviet satellites, DOD laser sites were prevented from illuminating Soviet satellites under routine operations. And, although the rule was in part established to protect Soviet NTM, no effort has been made to discern which satellites were NTM and which were not. A conservative interpretation of the Foster Memorandum, therefore, required that "not one laser photon" should fall on any Soviet satellite. Without knowledge of the damage thresholds of other foreign spacecraft (or, many U.S. satellites for that matter), the not-one-photon rule applies to

---

[58] "Foster Memorandum.

[59] *Ibid.* p. 1.

all satellites in orbit. As a statement of policy, then, the Foster Memorandum stipulates that *any satellite-directed laser illumination is likely to be considered interference unless permission is obtained beforehand.* Currently, the LCH is not aware of any DOD laser site conducting laser operations against foreign satellites.[60]

PROGRAM PARTICIPATION AND ASSESSMENT

At the present time, DOD laser sites participate in the Laser Clearinghouse program voluntarily. That is, while USCINCSPACE is the responsible agent charged with "authorizing" emission of laser energy from DOD laser sites into space, there is no formal enforcement mechanism requiring the sites to subscribe to the LCH program. The system is, however, effectively self-enforced. That is, if a site were to fire a laser into space without checking in with the LCH for predictive avoidance and happen to damage a satellite, the site would be solely responsible for the (potentially grave) consequences. On the other hand, if the site subscribes to the LCH program, (and if the guidelines are followed) USCINCSPACE accepts responsibility.

The success of the LCH program may be gauged in three ways. First, from the satellite owner/operator's standpoint, the program is successful because no accidental laser illumination events have been reported since the program was instituted in 1984.[61] Second, DOD participation within the DOD is high. Currently, the program subscribes 38 sites with non-waived lasers and over 100 sites with waived lasers. Of the 38 non-waived laser sites, about a dozen sites request predictive avoidance on a regular basis (at least once a week).[62] Recently, participation in the LCH program has extended beyond the DOD. Over the past year, the

---

[60] Telephone conversation with Lieutenant Thilenius, 18 February 1992.

[61] *Ibid.*

[62] *Ibid.*

Lawrence Livermore National Laboratory (operated under contract to the Department of Energy), which has attempted to apply powerful lasers originally developed for isotope separation to astronomical guide star applications,[63] has made use of the LCH for predictive avoidance support.[64]

It is possible that more non-DOD laser operators may make use of the LCH as they become aware of it, but these operators are not currently required to participate in the program. A quick calculation shows that the peak brightness of the lasers currently used for laser ranging greatly exceeds the SPADOC Laser Clearinghouse waiver threshold.[65] Consequently, these devices could be damaging to satellite optical sensors, but laser operators for NASA's Crustal Dynamics Program do not make use of the LCH.[66] A similar calculation for astronomical guide star lasers suggests that these devices are potentially damaging to space sensors as well.[67]

A third measure of success may relate to how well the laser site operators are supported. Operators of the LCH view their job as serving the laser sites, trying to make the system as transparent to them as possible. In many cases, the laser sites are permitted to

---

[63] Graham P. Collins, "Making Stars to See Stars: DOD Adaptive Optics Work is Declassified," Physics Today, February 1992, p. 20.

[64] "Laser to Create Star, Assist Astronomers," The Newport (R.I.) Daily News, January 27, 1992, p. A5; confirmed by telephone conversation with Lieutenant Thilenius, 18 February 1992.

[65] With a pulse energy of 100 millijoules and a pulse length of 150 picoseconds, the peak power of typical ranging laser pulses is 667 megawatts. If the half-angle beam divergence is 50 microradians, the laser brightness is 85 x 10^{15} watts per steradian. This value exceeds the LCH waiver threshold by over six orders of magnitude.

[66] Telephone conversation with Dr. John J. Degnan, Director, Crustal Dynamics Program, NASA Goddard Space Flight Center, 6 January 1992.

[67] Welch, et. al. suggested (see discussion in chapter 2) that a 106 millijoule laser with a 69 microsecond pulse length would be appropriate for astronomical sodium guide star work. The equivalent peak brightness of such a laser (assuming a 5 microradian half-angle beam divergence) is 19.6 x 10^{12} watts per steradian. If the laser pulses at 200 pps, the average brightness is 267 x 10^{9}, also exceeding the LCH waiver threshold.

calculate their own laser operating intensity values used in the LCH waiver determination. The LCH is also in the process of upgrading the predictive avoidance process. Even though the LCH reports better than ninety percent rate of approval for requested predictive avoidance windows, it has worked with the laser sites to reduce the effect of the remaining ten percent in some special cases.[68] For example, the LCH has permitted the illumination of selected, non-optical U.S. satellites in order to expand the laser firing windows for high-priority laser tests. The LCH is also currently installing an upgraded version of the predictive avoidance code which permits threshold damage curve parameters to be entered for each active (U.S.) satellite in the catalog.[69] Interviews with a number of laser site operators[70] suggest that they are generally satisfied with the support provided and the low level of administrative burden imposed by the LCH.

With the increase in testing of high-energy lasers and the increase in the number of U.S. and foreign satellites, the JCS has in the past perceived the need to make the LCH program mandatory for DOD laser site operators.[71] A draft DOD directive for the purpose of formalizing the Laser Clearinghouse program was last circulated for comment in 1989, though the proposal was rejected by OSD as imposing an unnecessary burden on laser operators.[72] A

---

[68] The LCH reports that of the roughly 7000 space objects in the current space catalog, only seven percent are active. As a result, their requests for predictive avoidance are fulfilled in 90-95 percent of the cases, even with the assumption that all satellites are laser vulnerable. Telephone conversation with Lieutenant James Thilenius, 5 December 1991.

[69] Lieutenant Thilenius, 18 February 1992.

[70] Interview with Dr Brian E. Edwards, MIT Lincoln Laboratory, Lexington, MA, 3 January 1992; telephone conversations with Major John Anderson, Phillips Laboratory, Starfire Optical Range, Kirtland AFB,NM, 6 January 1992 and Mr Harold Newby, Phillips Laboratory, Malabar Test Site, FL, 27 November 1991.

[71] "DOD Directive on Preventing and Reporting ... ," JCSM-169-87.

[72] Memorandum for the Joint Chiefs of Staff, "Proposed DOD Directive on Prevention and Reporting Laser Damage to Space Assets," Acting Deputy Director, Defense Research and Engineering (Test and Evaluation), 18 August 1989.

formalized and accepted DOD program could, however, form a model for a broader control mechanism encompassing non-DOD laser systems in the future.

LASER ILLUMINATION POLICY CONSIDERATIONS

The foregoing discussion of current Laser Clearinghouse procedures, U.S. administration policies for space and ASAT, and space law establishes a number of interests which would be served by a laser illumination policy. From these interests, three principle goals for a U.S. laser illumination policy emerge: (1) protection of U.S. space assets, (2) promotion of peaceful international cooperation in the use of space, and (3) preservation of future U.S. technological options (to include possible laser imaging of satellites).

PROTECTING U.S. SPACE ASSETS

In addition to military space systems operated for national defense, the U.S. has established commitments to supporting space exploration and research, environmental monitoring, and to promote commercial applications in space. A first priority for a U.S. laser illumination policy would be to protect our own immense investment in space systems from illumination by both domestic and foreign laser systems. While the USSPACECOM Laser Clearinghouse program contributes to protecting satellites from DOD lasers through the voluntary participation of DOD laser site operators, there are no requirements for non-DOD U.S. laser operators (e.g., government agencies or university researchers) to participate in the program--much less non-U.S. laser system operators.

U.S. laser illumination policy must ensure that U.S. space assets are not damaged by foreign lasers, whether or not the illumination is intentional. The U.S. military has reportedly taken steps to harden its satellites from hostile laser illumination, but as mentioned in the previous chapter no plans have been made to protect civil remote sensing or meteorological spacecraft even from inadvertent laser illumination. The primary reason cited for not implementing such measures on U.S. civil spacecraft is their high cost. International agreements placing minimal controls on laser emissions from ground sites (such as that followed under the DOD Laser Clearinghouse program) would contribute to minimizing accidental illumination of U.S. (and foreign) space assets.

On the other hand, if U.S. policy were to permit laser illumination of foreign spacecraft for surveillance or other purposes. While U.S. military satellites might be prepared for hostile illumination by a foreign laser, U.S. civil or commercial spacecraft would not. And, while military satellites might be able to survive such illumination, could they operate unimpeded under sustained harassment?

PROMOTING INTERNATIONAL COOPERATION IN SPACE

The U.S. Space Policy supports international cooperation in "maintaining the freedom of space for all activities that enhance the security and welfare of mankind." A U.S. policy for laser illumination should, therefore, support the use of lasers for peacetime military applications as well as provide for the noninterfering use of lasers in pursuit of non-military aims. The U.N. Charter (and, by inclusion, the Outer Space Treaty) permits the use of space for self defense which includes military surveillance. While adequate precedent for routine surveillance with radar has long been established, no such precedent exists for laser illumination. As a result, consultation between the laser and satellite operators may be required to work out a definition of what is considered harmful interference. Such a dialog, provided for under Article IX of the Outer Space Treaty, would promote the spirit of international cooperation in space.

An agreed-upon understanding of harmful laser interference could also serve to define which acts were truly provocative or militant and are not permitted. For example, low power laser illumination of certain non-optical satellites or with prior notification might be permitted, while unscheduled, high-power illumination by lasers tuned to blind overflying optical sensors would not. In this vein, the U.S. has had a long-standing reciprocal agreement with the Soviet Union not to interfere with each other's national technical means. If any form of laser illumination were considered harmful, it is not in the U.S. interest to illuminate these spacecraft: the risks associated with this action are potentially too great. However, if the spacecraft can be illuminated under conditions which are mutually understood to be non-harmful, the benefits obtained from such action may outweigh the risks. Again, the key question comes down to whether individual satellite owners perceive laser illumination to be a harmful act and therefore not permissible. This, in turn, may hinge on a mutually agreed upon interpretation of "harmful interference."

PRESERVING U.S. TECHNOLOGICAL OPTIONS IN SPACE

The third major policy goal is to protect the ability of the U.S. to develop and implement technology in support of its broader national goals. The development of laser sensors for space surveillance can support a number of military and civil sensing applications (as discussed in chapter 2). U.S. policy toward laser illumination should be scrutinized on the basis of how well it preserves opportunities for applying future laser developments in space. In supporting this policy goal, the laser illumination policy and the controls that may be applied should also not overly burden the laser system operators and developers. The current Laser Clearinghouse system appears to be fulfilling this promise; future controls should also not be made overly restrictive or burdensome.

CHAPTER IV

GROUND-BASED LASER THREATS TO SPACE SYSTEMS

Developing and assessing laser policy options for satellite imaging require interpreting the meaning of the term "harmful interference." In this chapter we attempt to quantify those laser illumination conditions which might justifiably be considered harmful to space systems. A better understanding of this technical issue enables one to construct operating guidelines (or, "rules of the road") for laser imaging.

In this chapter satellite components which are vulnerable to ground-based illumination are identified. For these components, damage mechanisms are reviewed and order-of-magnitude minimum damage thresholds are established. The illumination requirements for ground-based laser imaging systems are then compared with the damage thresholds. This process identifies which satellite components are likely to be threatened by ground-based laser imaging. Finally, these results are used to determine the classes of foreign satellites likely to be damaged by laser imaging and the conditions under which damaging interference might be experienced or avoided.

SATELLITE COMPONENT VULNERABILITIES TO LASER ILLUMINATION

Defining a maximum acceptable level of laser illumination for all spacecraft is extremely difficult owing to the differences in mission class, component design, and the material properties of spacecraft components themselves. However, because optical and infrared radiation interacts similarly with most spacecraft materials (i.e., as opposed to the way microwave radiation reacts with these same materials), one can develop order-of-magnitude damage estimates which are useful in framing a policy discussion for laser illumination. In this section, laser damage mechanisms and illumination thresholds for key satellite components are surveyed. The results of this survey indicate the sensitivity to damage of different spacecraft components, and suggest illumination thresholds at or above which damage is possible.

Thermal Balance

Since the void of space possesses a low effective temperature (about 4 degrees Kelvin), the outer surfaces of spacecraft are used to radiate excess heat to regulate internal spacecraft temperature.[1] However, because of the high-vacuum environment, convective cooling of space bodies is minimized and so exterior satellite surfaces which absorb laser radiation will heat up and transfer this heat to other spacecraft components by conduction.[2] Prolonged exposure of about 1.4 W/cm^2, or about ten times the total radiant intensity of the sun (i.e., ten "sols"),[3] could overload the thermal control systems of most satellites.[4] Callaham and Tsipis calculate, for example, that a blackbody absorber exposed to ten sols of radiation reaches an equilibrium temperature of 705 Kelvin which is sufficient to damage many electronic devices.[5] Lead-tin solder, used to electronically and mechanically bond such components melts at about 673 K. Satellites could be damaged at somewhat lower laser flux levels, however; it has been suggested that a laser intensity as low as 0.3 W/cm^2 (about two sols) might upset a satellites'

---

[1] Martin Donabedian, "Cooling Systems," W.L. Wolfe and G.J.Zissis, eds., The Infrared Handbook (Washington, DC: GPO, 1978), chapter 15, p. 47.

[2] Ronald H. Ruby, et al., Laser ASAT Test Verification, A Study Group Report to the Federation for American Scientists (n.p.: 20 February 1991), pp. 24-25.

[3] Average total exoatmospheric solar irradiance at the top of the earth's atmosphere is 1353 watts per square centimeter. Gwynn H. Suits, "Natural Sources," W.L. Wolfe and G.J.Zissis, eds., The Infrared Handbook (Washington, DC: GPO, 1978), chapter 3, p. 34.

[4] M. Callaham and K. Tsipis, High Energy Laser Weapons: A Technical Assessment, Program in Science and Technology for International Security Report No. 6 (Cambridge, MA: Massachusetts Institute of Technology Physics Department, November 1980), p. 35.

[5] *Ibid.*

normal operation if this flux were continuously illuminated for a period of several tens of seconds.[6]

To facilitate the task of maintaining thermal balance, satellites are often wrapped with optically transparent polymers such as Mylar, Kapton, or Teflon sheets which are backed with aluminum, silver, or gold. These thermal control wraps help manage spacecraft temperature by reflecting optical energy (sunlight is concentrated in the visible wavelength band) and reradiating absorbed heat, in the form of infrared radiation, away from the spacecraft body. Ruby, et. al. have estimated that about 10 J/cm^2 of incident visible or infrared laser energy (e.g., a laser intensity of 10 W/cm^2 applied for one second) would be required to destroy Kevlar thermal wrap.[7] Owing to re-radiation of absorbed heat, it would take a laser producing one sol of flux (0.14 W/cm^2) more than 70 seconds of continuous illumination to damage Kevlar or similar thermal wrap materials. Consequently, lasers producing one tenth of a solar constant flux should not be a threat to thermal control wrapping materials so long as the illumination time were limited to a minute or less.

A spacecraft owner/operator concerned about thermal damage would monitor the temperature of critical spacecraft components. Callaham computes that the equilibrium temperature of a blackbody illuminated with 0.1 sol average irradiance is 396 K, only about 100 K higher than the spacecraft's normal operating temperature.[8] And, the fact that the earth's reflected solar radiation (earthshine) can be ten percent or more of the solar contribution to spacecraft heating,[9] suggests that total laser irradiation less than 0.01 sol (0.0014 w/cm^2)

---

[6] Richard L. Garwin and Theodore Jarvis, Jr., "Non-ABM Technologies," Paul Doty, ed., Defending Deterrence (New York: Pergamon-Brassey's, 1989), pp. 91-92.

[7] Ruby, p. 27.

[8] Callaham and Tsipis, p. 38.

[9] Donabedian, pp. 54-55.

might be indistinguishable from natural sources of radiation from a thermal management standpoint.

Structural Damage

At much higher flux levels, laser light can damage spacecraft structural members such as booms, spars, and the skin of the spacecraft. Ruby et. al. shows that about 200 joules/cm^2 (40 seconds of illumination at 5 W/cm^2) are needed to melt through a 0.5 mm thick aluminum plate.[10] This is about ten times the total fluence required to destroy thermal wrap material. On the other hand, if enough laser energy is deposited on a surface quickly enough (a few microseconds), the illuminated surface may explosively evaporate causing a mechanical recoil. If this recoil impulse is strong enough, the bulk material may crack or tear. The American Physical Society study on directed energy weapons reports that 5 kJ/cm^2 is sufficient to rupture a 3 mm thick aluminum plate, and 800 J/cm^2 is sufficient for a 0.5 mm thickness.[11] Callaham and Tsipis suggest it may take as little as a few hundred joules to crack aluminum in a single short laser pulse, and perhaps significantly less if the structure is already under mechanical stress.[12]

Solar Panels

While solar cells are able to withstand prolonged and direct exposure to the sun, short high-energy impulses of laser light can shatter or vaporize their glass covers. This effect may occur at a fluence of about 5 J/cm^2.[13] Continuous exposure to flux levels above 10 sols for

---

[10] Ruby, p. 27.

[11] N. Bloembergen and C.K.N. Patel, "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons," Reviews of Modern Physics, vol. 59, July 1987, part II, p. 129.

[12] Callaham and Tsipis, p. 32.

[13] Ruby, pp. 28-29.

several tens of seconds may melt solder connections or damage structural members, as discussed above.

Optical Sensors

Lasers can interfere with space-borne optical sensors in a number of ways. When the laser power entering the optical system exceeds the signal level the sensor was built to accommodate, the sensor may be temporarily blinded. This effect may manifest itself in the detector material, as is the case when well capacity of a charge-coupled device (CCD) detector is exceeded and the detector "blooms", or when amplifier circuitry and analog-to-digital converter (ADC) circuits saturate. This type of interference, also known as "dazzling", depends on the illumination power level and the sensor design, and may not cause permanent damage. If, on the other hand, the laser power level is sufficient to heat the detector surface to the point where the electrical or material characteristics of the detector are altered, the detector performance may be permanently degraded or destroyed. Damage thresholds for detector materials are are usually specified at the point at which the detector is visibly and irreversibly damaged (e.g., melts or mechanically deforms)[14] or when the material detectivity (known as D*, "dee-star") drops by one-half.[15] While the damage criteria differ, experience indicates that the fluence levels for D* degradation and melting (both irreversible processes) are within an order of magnitude of each other.[16]

As a class, optical sensors can be--by many orders of magnitude--the most sensitive satellite components to laser illumination. In-band sensor damage or interference occurs when

---

[14] F. Bartoli, et al., "Irreversible Laser Damage in IR Detector Materials," Applied Optics, vol. 16, November 1977, pp. 2934.

[15] Telephone conversation with Dr. Koto White, USAF Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH, 6 January 1992.

[16] *Ibid.*

laser light is tuned to the passband of the sensor's optical train and a significant portion of the light energy falling on the collecting aperture is focussed on the detector's photosensitive surface. Because the collecting optics will concentrate all the incident laser light onto a single detector element in the focal plane, even tiny amounts of laser light can do serious damage to optical detector materials. For example, while the damage threshold of detector materials themselves are on the order of 1J/cm^2, this same detector in the focal plane of a high gain earth-sensing optical system could be permanently damaged with as little as 10^{-9} J/cm^2 incident on optical collector.[17] While this damage figure is representative of current-technology remote sensing satellites, a large (several orders of magnitude) variability in this number may result from differences in laser wavelength, detector damage threshold, and many details of the sensor system design. Further, deployments of even higher gain optical systems may lower the damage threshold still further.[18]

At much higher illumination levels, laser light may cause physical damage to optical coatings, sensor optics, and housing structures. Physical damage could arise from a number of mechanisms. For example, impulsive shocks may cause optics to shatter. Longer-term energy absorption may cause the sensor package to heat up until the weakest component (e.g., a solder connection) fails. Damage to optical coatings, for example, can occur at fluence levels of 1.0 J/cm^2 while fluences five times this figure can cause optical elements to shatter.[19] Sustained, relatively moderate levels of irradiation (a few watts per square-centimeter over tens of seconds) may cause the instrument's housing and mechanical structure to deform, degrading

---

[17] A theoretical (maximum) optical gain of 10^9 is typical of current-technology spaceborne earth remote sensing systems. Damage thresholds for typical sensor materials and selected high gain optical systems surveyed in the Appendix.

[18] Ruby considers an optical gain of 10^{10} J/cm2 (see Ruby, p. 28). Discussion in the Appendix suggests that an optical gain of 10^{12} may be possible.

[19] Ruby, pp. 28-29.

the instrument's optical performance, as could short high-energy pulses which impart an impulsive load.

The optical sensors susceptible to the lowest levels of laser illumination are those which view the earth and operate in the wavebands which pass laser wavelengths. Because of the optical transmission properties of the atmosphere, satellite systems viewing earthward have a high potential for detector damage since the lasers most useful for satellite sensing from the ground must also operate in these same "windows" of good optical transmission. The class of earth-viewing satellite systems--which includes earth resource monitoring, mapping, meteorology, some nuclear burst detection, and military surveillance and reconnaissance satellites--often carry sensors with the highest optical gain possible to maximize their sensitivity to light, further increasing the possibility of damage from laser light.[20]

Not all earth-viewing sensors are sensitive to laser illumination, however. Certain launch detection satellite systems, for example, may be less susceptible to laser radiation since their primary sensing bands are at wavelengths where the atmosphere is relatively opaque.[21] There, sensitivity to low-power laser light emanating from the ground is presumably limited to out-of-band damage effects caused by absorption in optical components rather than through direct irradiation of the focal plane. Further, certain wavebands (e.g., 0.70-0.74 and 1.1-1.3 μm bands) have either marginal or unexploited utility for earth-sensing missions such as monitoring vegetation growth.[22] Poor detection sensitivity exhibited by optical detectors at

---

[20] See, for example, the Appendix, Table XI, "Optical Gains and Equivalent Sensor Damage Thresholds."

[21] Ashton Carter, "The Current and Future Military Uses of Space," Joseph S. Nye and James A. Shear, eds., Seeking Stability in Space (Lanham, MD: University Press of America, 1987), p. 52.

[22] Compton J. Tucker, "A Comparison of Satellite Sensor Bands for Vegetation Monitoring," Photogrammetric Engineering and Remote Sensing, vol. 44, November 1978, p. 1369; David S. Simonette, "The Development and Principles of Remote Sensing," Robert N. Colwell, ed., Manual of Remote Sensing (Falls Church, VA: American Society of Photogrammetry, 1983), vol. 1, chapter 1, p. 24.

some wavelengths may also limit the extent to which these bands will be utilized for space-based remote sensing.[23]

Space-borne optical sensors which do not normally view the earth would not be threatened by the low levels of laser illumination which could ordinarily harm earth viewing optical sensors. Under normal spacecraft operation, alignment sensors such as star and earth limb sensors (used to sense the positions of reference stars and the earth horizon, respectively) are not pointed toward earth. Even though earth limb sensors may view a few degrees above and below the horizon, no ground-based laser would be fired at a correspondingly low elevation angle above its horizon due to atmospheric propagation losses and range safety considerations. Consequently, the vulnerability of such sensors to laser radiation occurs at illumination levels above which thermal or structural damage is a concern. Similarly sun sensors, which are used to orient the satellite's solar array for optimum collection efficiency, are insensitive to interference from ground-based lasers as are other high gain optical systems which may be used for satellite surveillance (e.g., SDIO's Space Surveillance and Tracking System) or astronomy (e.g., Hubble Space Telescope) which do not point earthward.

Laser Illumination Threat Overview

Table V summarizes the laser illumination threats to satellite components discussed above, associating ball park damage threshold values with each of the component vulnerabilities. Figures computed in the Appendix specifically for lasers used for ground-based satellite imaging suggest that in-band damage to optical detectors exhibit the minimum level damage threshold in the vicinity of 10^{-9} J/cm^2 for pulsed lasers, while their minimum threshold for irradiance is about 10^{-8} W/cm^2. Comparing these figures with damage thresholds

---

[23] The bandgap cutoff for intrinsic silicon detectors at 1.1 μm, for example, severely limits the detectability of light for these sensors in the 1.1-1.3 μm wavelength band. See, for example, RCA Corporation, Electro-Optics Handbook, Technical Series EOH-11 (Lancaster, PA: RCA Corporation, 1974), pp. 145-172.

TABLE V

LASER THREAT OVERVIEW

COMPONENT	DAMAGE TO	DAMAGE THRESHOLDS (PULSED, J/CM^2)	DAMAGE THRESHOLDS (AVG., W/CM^2)
SENSOR PAYLOAD	DETECTORS	10^{-9}	10^{-8}
	OPTICAL COATINGS	1	–
	OPTICS	5	–
SOLAR CELLS	COVER GLASS	5	–
	SOLDER CONNECTIONS	–	1
THERMAL BALANCE	THERMAL WRAP	–	1
STRUCTURE	1 MM AL. PLATE	1,600	30
EYE HAZARD	RETINA	10^{-5}	10^{-4}
	CORNEA	1	–
SKIN BURNS	SKIN	15	–

Sources: See text.

for other spacecraft components clearly demonstrates the extreme sensitivity of optical sensors to laser damage: high gain optical sensors can be damaged at laser pulse energy levels a billion times less than that needed to damage optical coatings (1 J/cm^2) or to shatter glass (5 J/cm^2), and 10^{12} less than that needed to do structural damage (1,600 J/cm^2). Optical sensor damage thresholds for repetitively pulsed or continuous-wave (cw) laser illumination are one hundred million times less than the flux levels which could begin to threaten satellite thermal balance.

Damage thresholds for the human eye and skin are included for comparison. Although the eye is much less sensitive to damage than the highest gain optical sensors, precautions would have to be taken if spacecraft containing astronauts (or cosmonauts) were to be illuminated with energy levels exceeding ten micro-joules per square-centimeter, or power levels exceeding 100 micro-watts per square centimeter.

SENSING REQUIREMENTS FOR GROUND-BASED LASER IMAGING

The amount of laser light incident on a satellite needed to image that satellite depends on which laser imaging technique is used. For example, because the guide star imaging system uses a laser to excite sodium atoms in the earth's atmosphere, the amount of laser power needed for satellite imaging is incidental to how much actually hits the satellite. And, because of spreading (diffraction) in the guide star laser beam, the amount of laser light actually striking a satellite is inversely proportional to the square of the satellite's range.

As originally conceived and implemented at the Firepond site, a wideband coherent imaging system requires that a certain minimum amount of backscattered laser energy is collected at the ground-based receiver (possessing a fixed aperture size). Consequently, the required transmitter power must generally increase as the fourth power of satellite range to compensate for diffraction losses in the light's travel out to the target satellite and back. This implies that the amount of laser power actually striking the satellite must increase as the square of the satellite's range to compensate for the diffraction losses on the light's return trip to the receiver.

In the case of laser speckle imaging, on the other hand, the effective size of the receiver elements on the ground may be made as large as the scale size of backscattered laser speckle pattern--a dimension which increases as range of the satellite increases.[24] As a result, so long as the laser receiver element sizes are scaled to the satellite's range in the appropriate way, the amount of laser light falling on the spacecraft for laser speckle imaging can be made to be a constant value, independent of range.

The amount of light hitting a satellite needed for flood beam imaging depends on whether or not adaptive optics compensation is employed in the receiver. If adaptive optics is used to compensate for atmospheric distortions in the downlink (receiving) leg, the amount of light striking the satellite may remain constant with range. This is because, as in the case of laser speckle imaging, the effective detector size can be increased to match the size of the "information cells" in the image which grows with target range. Consequently, the laser power needed for flood light imaging (with adaptive optics) is independent of range.[25] On the other hand, if no adaptive optics is implemented on the downlink and digital processing is used to correct the images for atmospheric distortion, the amount of laser light hitting the satellite being imaged increases as the square of the range. This is because the size of information cells needed to recover good images with signal processing depends on the scale size of the atmospheric distortions--a value which does not scale with satellite's range.

Satellite laser fluence and irradiance values for the sodium guide star, flood light, laser speckle, and wideband coherent laser imaging systems are summarized in Table VI. Columns four and five establish the laser energy and power densities, respectively, for each technique based on the laser device data contained in Table I (chapter 2) at a satellite altitude of 1000

---

[24] The scale size of a laser speckle "lobe" on the ground produced by an object of width w, illuminated by a laser of wavelength λ, at a range R is given by $\Delta s = \lambda R/w$. Since the speckle lobe characterizes an area of minimal image information content, there is marginal value in sampling the speckle lobe more than once or twice a speckle lobe width. Hence, the detector sample sizes can be scaled according to the range of the target.

[25] If a laser guide star system is used to drive the adaptive optics, the total incident laser energy needed to image the satellite will be increased by the guide star laser's light. Therefore, because the guide star illumination on the satellite drops off as the reciprocal square of the range, the total (guide star plus flood light) laser energy needed to image will decrease somewhat with range.

kilometers.[26] A five microradian (one arc-second) half-angle beam divergence is assumed for each laser illuminating beam. Since this is a smaller beam divergence than is usually achieved by lasers in practice today, it provides an approximate upper bound on the amount of laser light hitting the satellite for each laser imaging technique. Using the same figure for all laser wavelengths is consistent with optimizing laser transmission up through the earth's turbulent atmosphere. That is, since the diffraction-limited beam divergence is limited by the atmospheric coherence length r_0, and this parameter is approximately proportional to wavelength, setting the transmitting aperture size equal to r_0 will produce approximately the same diffraction limited beam spread for all wavelength lasers.

In citing the energy and power density figures in Table VI, it is assumed that these illumination levels are adequate for imaging a satellite at 1000 km range. This assumption is reasonable since each system has either successfully operated, or has been designed to operate, at this range or greater (see discussion in chapter 2; also, Table I) with an illuminating beam divergence greater than or equal to 5 microradians. The fact that the flood light and wideband coherent systems have already been successfully used to image satellites from the ground suggests that these figures may be non-minimal, and may provide conservative upper bound to the laser illumination levels need to image satellites using these techniques. Future

---

[26] Laser fluence (energy density) incident on the satellite is computed from

$$F_{INC} = \frac{1}{\pi} \frac{E_T}{\theta^2 R^2}$$

where E_T is the laser pulse energy, θ is the (half-angle) beam divergence and R is the range from laser to the satellite. Average laser irradiance on the spacecraft (power density) is similarly computed from

$$I_{INC} = \frac{1}{\pi} \frac{P_{AV}}{\theta^2 R^2}$$

where P_{AV} is the average emitted laser power.

TABLE VI

SATELLITE ILLUMINATION LEVELS FOR LASER IMAGING

IMAGING TECHNIQUE	WAVELENGTH (μm)	AVERAGE EMITTED POWER (W)	FLUENCE AT SATELLITE (J/CM^2)[a]	IRRADIANCE AT SATELLITE (W/CM^2)[a]	RANGE FACTOR
SODIUM GUIDE STAR	0.589	1060	1.3E-7	1.3E-3	R^{-2}
FLOOD LIGHT - WITHOUT A/O	0.694	800	1.0E-4	1.0E-3	R^{+2}
- WITH A/O	0.694 0.589	800 1060	1.0E-4 1.3E-7	1.0E-3 1.3E-3	1
LASER SPECKLE	1.315	600	7.6E-5	7.6E-4	1
WB COHERENT	11.17	600	7.6E-5	7.6E-4	R^{+2}
MIRACL-ASAT	3.8	2.2E+6	-	2.8	1

a. Measured at 1000 km range; 5.0 microradian (half-angle) beam divergence assumed.

Sources: Author's calculations, see text.

modifications to the system configuration or future improvements in component technologies may make it possible to reduce the laser illumination requirements for all the laser imaging techniques.

The range factor (column six) reflects the general dependency of the on-satellite illumination level with range R discussed above. The flood light technique has range factors of one and R^2, depending on whether or not adaptive optics is used for receiver compensation.

For sake of comparison, parameters for the Mid-Infrared Advanced Chemical Laser (MIRACL), a high energy deuterium-flouride (DF) chemical laser located at White Sands

Missile Range, New Mexico, are listed in the last row of Table VI. In 1986 the MIRACL device was mated with a laser beam director in order to test high power beam propagation through the atmosphere. If used as an directed energy antisatellite (ASAT) laser, the range factor for MIRACL would be one because the amount of laser power needed to destroy a given satellite is constant, independent of its range. With a 5.0 microradian beam divergence, MIRACL (a continuous wave device) would be able to deposit about 20 solar constants of flux (2.8 W/cm^2) on a satellite at one thousand kilometers range.[27] The average irradiance levels given in Table VI show that, at 1000 km altitude, imaging lasers deposit three orders of magnitude (a factor of one thousand) less optical power density than MIRACL configured as an ASAT. This comparison suggests that the ground-based imaging laser systems, as they are configured here, are not MIRACL-class ASAT threats to low earth orbit satellites.

More powerful laser illuminators are not necessarily required for imaging satellites at higher altitudes. An increased transmitting aperture combined with adaptive optics (perhaps with the use of a guide star laser) to correct atmospheric distortions on uplink can be used to maintain an constant desired spot size at the target range. For example, a one kilowatt laser projected into 5.0 microradians (half-angle) produces a spot 5 meters radius at 1000 km altitude. The average beam irradiance at this range is 1.27 x 10^{-3} W/cm^2, or about one one-hundredth of the equivalent solar flux. If the beam transmitter is constructed and operated to produce a 5 meter spot at any other altitude by appropriately adjusting the beam divergence, the laser irradiance at that altitude is the same.

The ability to correct for distortions in increasingly larger transmitting apertures, of course, implies that lasers used to illuminate more distant satellites may be capable of producing correspondingly small beam sizes at lower altitudes. For example, a one kilowatt

---

[27] Assuming MIRACL transmits a beam with 2.2 megawatts of output power and a 5.0 microradian beam divergence suggests it could deposit 2.8 W/cm2 (20 sols) on a satellite at a range of 1000 km.

laser atmospherically compensated to produce a 5 meter spot at 20,000 km altitude (which requires a fully-corrected 4.0 meter diameter transmitter at one micrometer wavelength) could produce a 0.25 meter spot with a 0.5 W/cm2 average beam intensity (about 3.5 solar constants) at 1000 km altitude. At 200 km altitude, this same laser system might produce a 0.05 meter spot with an on-target beam irradiance of 12.7 W/cm^2 (about 100 solar constants), posing a threat to thermal wrap material, solder connections, and perhaps (with enough dwell time) even aluminum structural members. As a consequence, laser-beam transmitters designed for imaging satellites at long ranges may, at shorter ranges, be very effective ASAT weapons.

In the interests of reassuring foreign satellite owners that laser imaging systems do not represent an ASAT threat (at any altitude), it may be useful to restrict the maximum beam brightness of laser imaging systems. For example, one might consider the equivalent of one solar constant (0.14 W/cm^2) to be the maximum acceptable laser fluence deposited on any satellite. If the minimum satellite orbital altitude is 170 km, then the corresponding maximum allowable laser brightness is about 40×10^{12} W/sr.[28]

The imposition of a maximum allowable laser brightness to limit laser ASATs would, however, also restrict the operating range of laser imaging systems to low earth orbit satellites only. The laser speckle imaging technique, for example, requires 760 microjoules per square centimeter power density (that is, 600 watts of laser power contained in a beam of 5 meters radius, see Table VI) to image a satellite at the any range (the range factor for laser speckle imaging is one). The maximum range at which a 40×10^{12} W/sr beam could produce this illumination level is 2300 km.[29] Similar restrictions might apply to the flood light and

---

[28] Laser irradiance I at range R is related to the beam brightness through the expression $I = B/R^2$. The minimum allowable laser brightness becomes $B = I_{MAX} R_{MIN}^2 = 0.14\ W/cm^2 \times (170 \times 10^5\ cm)^2 = 40 \times 10^{12}$ W/sr.

[29] Solving for the beam brightness expression for R, and substituting the values for I (power density) and B (beam brightness), gives R = 2294 km.

wideband coherent imaging techniques. Guide star imaging is not limited in the same way because its laser light is not used to illuminate the satellite directly.

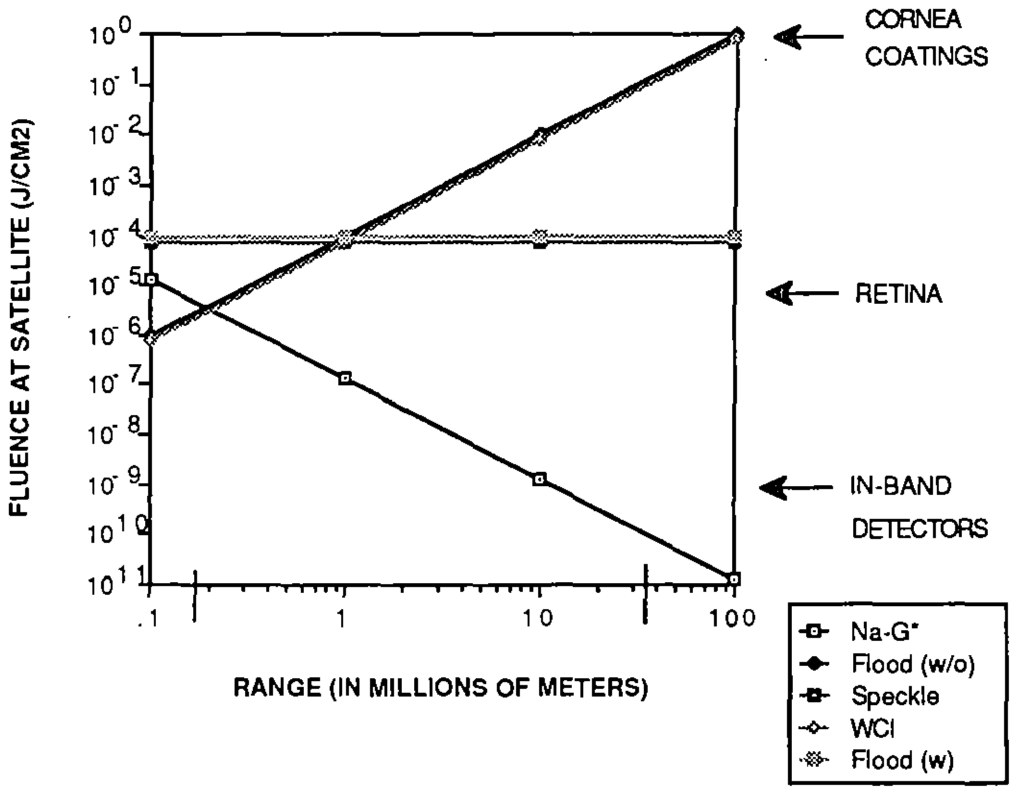
GROUND-BASED LASER/VULNERABILITY OVERLAYS

Figure 4 plots, as a function of satellite range, the required laser fluence (energy density) needed to perform each of the four laser imaging functions described above. This figure offers an easier way to visualize the information contained in columns four and six in Table VI: each plot specifies the energy density deposited by each ground-based laser as a function of satellite range (indicated in millions of meters, or, thousands of kilometers). Because the laser speckle imaging and flood light with adaptive optics ["Flood (w)" in figure legend] systems operate with the roughly same average emitted power and have the same range factor, the curves for these two techniques are nearly superimposed. Similarly, the curves for the wideband coherent and flood light without adaptive optics ["Flood (w/o)" in legend] systems are nearly superimposed. The two large hash marks on the abscissa indicate the range of satellite altitudes from 170 km (extreme low-earth orbit) to 36,000 km (geosynchronous orbit). The arrows down the right side of the plot frame indicate the fluence levels which cause in-band sensor damage to high gain optical systems, damage to optical coatings, and damage to the human cornea and retina.

The figure shows that the flood light (ruby laser), speckle imaging (iodine laser), and wideband coherent imaging (CO_2 laser) systems require satellite fluence levels which threaten potential in-band sensor damage at all satellite ranges. However, because the cornea absorbs infrared radiation, the CO2 wideband coherent imaging system is not an eye safety hazard except for systems operating at super-synchronous satellite ranges. The sodium guide star system, on the other hand, appears to be non-threatening to the retina (at all satellite ranges) and to in-band sensor damage at 0.589 μm wavelength, for satellite sensors beyond 10,000 km

FIGURE 4

DAMAGE POTENTIAL FOR PULSED LASERS



range. Since some optical sensors may possess less optical gain, some optical satellites at lower altitudes may not be threatened by the guide star system as well.

While the single pulse energies radiated by each system represent damage threats to sensitive earth-viewing optical sensors, it is important to point out that none of these laser imaging systems are single-pulse ASAT threats to non-optical satellites. For satellite ranges less than 3000 km, for example, the fluence levels for all techniques are below 10^{-3} J/cm^2. This value is six to seven orders of magnitude below pulsed damage thresholds for aluminum (about 1600 J/cm^2, c.f. Table V), and three to four orders of magnitude less than that needed to shatter the cover glass on solar cells (5 J/cm^2).

Damage Potential--Average Power Effects

In a similar fashion to the previous figure, Figure 5 plots the average laser power density deposited at satellite ranges for each of the laser imaging systems considered. For the flood light system using adaptive optics, it is assumed that a sodium guide star is used to drive the adaptive optics system. Therefore the plotted flux value [see "Flood (w)" curve in Figure 5] is the sum of the sodium guide star and the ruby flood light laser fluxes. The collection of plots shows that all ground-based laser imaging systems deposit an average of less than one equivalent solar constant of power density on satellites below 15,000 km range. For satellites at ranges less than 6000 km (but greater than 170 km), all systems deposit less than 0.6 W/cm^2 or 40 percent of the equivalent solar flux. For satellites at these ranges, it seems safe to conclude, these ground-based laser systems do not pose a thermal ASAT threat so long as the dwell times are restricted to a few tens of seconds and the pulse repetition rates (and, so, their average transmitted powers) are not significantly increased.

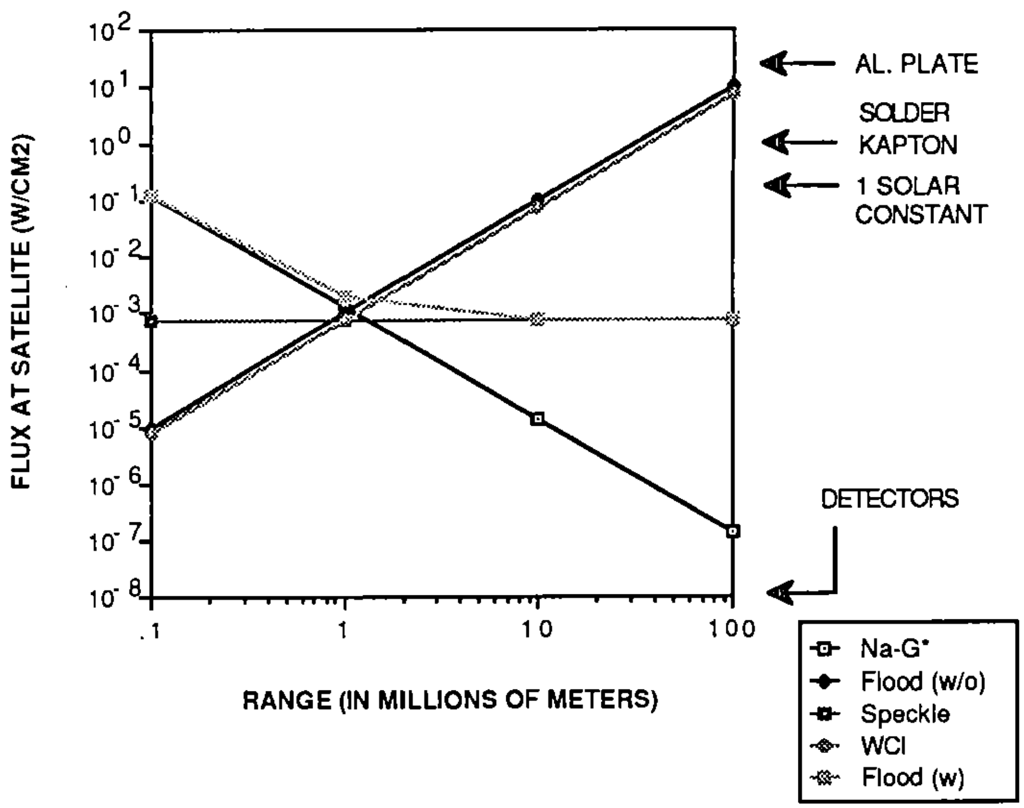
Note that the one kilowatt sodium guide star technique presents the greatest threat to satellites at the lowest altitudes. For satellites at 170 km altitude (the perigee for Soviet fourth-generation photoreconnaissance satellites[30]), the flux level for direct illumination by a 1060 watt sodium guide star is 59 milliwatts per square centimeter--about 0.4 sol of equivalent optical flux. If one wished to establish a "sure safe" maximum satellite illumination level of 0.1 sol, say, which should permit direct illumination for a complete low earth orbit satellite pass (two to three minutes), the incident power level of the guide star laser would have to be lowered. Since the beam brightness of a 1060 watt sodium guide star laser with a 5.0 microradian half-angle beam divergence is 13.5 x 10^{12} W/sr, the corresponding maximum

---

[30] Paul B. Stares, Space and National Security (Washington, DC: The Brookings Institution, 1987), p. 16.

FIGURE 5

DAMAGE POTENTIAL FOR AVERAGE LASER POWER DENSITY



allowable beam brightness for sure-safe operation would be one quarter of this figure, or about 3.4 x 10^{12} W/sr.[31]

For satellites at ranges of 15,000 km or more, on the other hand, the wideband coherent imaging and the flood light without adaptive optics systems may deposit an average laser flux greater than 0.14 W/cm^2 (one sol). This condition results, of course, because of the need to transmit increasingly stronger laser pulses to compensate for the R^2 propagation losses

---

[31] A reduction of on-target beam intensity could be be obtained, for example, by pointing the sodium guide star laser a few microradians behind the satellite.

on the return path. In order to contemplate wideband coherent imaging systems for applications to high earth orbit satellites, then, one would need to reconsider the design approach taken in developing the Firepond demonstration system. For example, one may wish to consider forming a proportionally larger receiver aperture as the satellite range increases (say, by using a shorter wavelength laser and adaptive optics in the receiver aperture). The fact that the flood light with adaptive optics and laser speckle imaging receivers are, by design, sized in proportion to the target satellite range means that, assuming the pulse repetition rate is held fixed, the deposited laser flux may be kept the same at all satellite ranges. Again, the sodium guide star system deposits the least power density at high altitudes because of its R^{-2} range factor.

IMPLICATIONS FOR GROUND-BASED LASER IMAGING OF SPACECRAFT

The results of the previous section suggest that ground-based laser imaging systems are not a thermal ASAT nor a pulsed laser ASAT threat (when they are operated as imaging devices) to satellites below 6000 km so long as the illuminated spacecraft are not carrying sensitive earth-viewing optical instruments. Since all the laser imaging systems considered illuminate their targets with less (and, in some cases much less) than 10^{-2} J/cm^2 energy density and 10^{-1} W/cm^2 power density at these ranges, these imaging techniques may offer adequate safety margin to pose no damaging interference threat to non-optical satellites. On the other hand, operating fluence and flux levels for these systems are many orders of magnitude above the damage thresholds for in-band optical sensors. So, without further consideration, one would conclude that laser imaging systems are a potential threat to the normal operations of satellites carrying earth-viewing optical sensors.

Table VII lists selected satellites of the former Soviet Union and their on-orbit function.[32] The spacecraft are grouped into optical, non-optical, and laser-hardened satellite classes. The numbers in parentheses next to the names of Soviet spacecraft indicate the number of satellites nominally operating on orbit.[33] Those satellites in the optical satellite class ordinarily require earth-viewing optical or infrared sensors to perform their mission. Their fluence damage threshold (10^{-9} J/cm^2) reflects the assumptions that the laser wavelength is in-band to the sensor and the sensor is looking directly back into the laser beam. If the laser is tuned sufficiently out of the sensor's light sensitive band, incident laser light would be absorbed by otherwise transmissive optical elements and coatings. The lowest damage thresholds for non-optical satellites assume that the damage mechanism for average power is thermal balance (one equivalent solar constant of flux, or one sol); for pulsed effects the damage mechanism is assumed to be the shattering of glass covers on solar cells (5 J/cm^2). The third class of satellites, laser-hardened satellites, includes those spacecraft which were either designed to be illuminated by lasers or do not contain earth-viewing optical sensors nor solar panels (the Soviet RORSATs fall into this latter category, for example). The Kosmos geodesy satellites are known to carry laser retro-reflectors.[34] The retros are used to enhance the laser returns when illuminated by ground-based satellite ranging stations.

The classification of satellites by damage sensitivity shown in this table suggests that a large fraction of low-earth orbit satellites (classified as non-optical or laser-hardened) would not be expected to be harmfully interfered by low power laser illumination of the levels required by ground-based laser imaging techniques. Eight of the eleven Soviet military satellite

---

[32] The satellites listed in Table VII are taken to be representative of foreign civil and military spacecraft.

[33] Eric H. Arnett, "Antisatellite Weapons Issue Paper," AAAS Program on Science, Arms Control, and National Security, AAAS Publication No. 90-11S, January 1990, p. 2.

[34] Nicholas L. Johnson, The Soviet Year in Space 1990 (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), pp. 57-58.

TABLE VII

PRESUMED LASER DAMAGE SENSITIVITIES FOR SOVIET SATELLITES

SATELLITE DAMAGE CLASS	DEFINING DESCRIPTION	DAMAGE SENSITIVITY[a]	DAMAGE MECHANISM[b]	APPLICABLE SATELLITE TYPES[c]
OPTICAL	CARRIES EARTH-VIEWING OPTICAL SENSORS	10^{-9} J/CM^2 10^{-8} W/CM^2	IN-BAND SENSORS IN-BAND SENSORS	PHOTORECCE (3) METEOR 2/3 (5) KOSMOS E/WARN. (9) RESURS/OKEAN MIR/SALYUT
NON-OPTICAL	DOES NOT CARRY EARTH-VIEWING OPTICAL SENSORS	5 J/CM^2 1 W/CM^2	SOLAR CELLS THERMAL WRAP	KOSMOS SIGINT (7) EORSAT (3) KOSMOS COMM (27) MOLNIYA COMM (8) KOSMOS NAV (10) GLONASS NAV (24)
LASER HARDENED	CARRIES LASER RETROS, OR DOES NOT CARRY EARTH-VIEWING OPTICAL SENSORS NOR SOLAR CELLS	1600 J/CM^2 30 W/CM^2	IMPULSE DAMAGE TO ALUMINUM STRUCTURES AL PLATE MELTS	RORSAT (2) KOSMOS GEODESY (2)

a. Component pulse energy (J/cm^2) and average power damage (W/cm^2) thresholds shown in Table V.

b. See Table V.

c. Based on satellite mission descriptions in Paul B. Stares, Space and National Security (Washington, DC: The Brookings Institution, 1987), pp. 8-44; Nicholas L. Johnson, The Soviet Year in Space 1990 (Colorado Springs, CO: Teledyne Brown Engineering, February 1991); Eric H. Arnett, "Antisatellite Weapons Issue Paper," AAAS Program on Science, Arms Control, and National Security, AAAS Publication No. 90-11S, January 1990, p. 2.

classes are either non-optical or laser-hardened. In terms of numbers of satellites, 83 of the 100 normally operating on orbit are classified as non-laser sensitive for purposes of ground-based laser imaging. While many of the so-called optical satellites are potentially threatened by ground-based laser imaging operations, two of these mission classes are protected by bilateral non-interference treaty clauses with the Soviet Union. If one considers Soviet photoreconnaissance satellites as components of their national technical means,[35] their operations are protected by the ABM Treaty (and SALT II provisions) and because of their mode of operations (optical sensing), laser illumination would--without other cooperative or protective measures--be considered intentional acts of interference not appropriate for peacetime operations. Kosmos early warning satellites are protected by the provisions of the Prevention of Nuclear War Agreement. Consequently, intentional illumination of these satellites by in-band lasers would not normally be in the United States interest. Of course, possessing satellite-tracking laser illuminators gives the U.S. the capability to use these devices as optical harassment or disruption weapons if it so chooses. Since a large class of Soviet and other foreign satellites are not laser sensitive--and, the safety margins for non-optical satellites are significant--the United States should not feel that laser imaging imposes harmful interference to their normal operation.

The fact that the peak laser illumination level exceeds the presumed in-band damage sensitivity figure does not guarantee that such a laser is a threat to the operation of what is classified as even a laser-sensitive optical satellite. First of all, the detector damage threshold values used in the appendix were chosen to be illustrative, not definitive. In-band sensor damage thresholds could be higher or lower for any given satellite sensor; though, by considering earth-viewing remote sensing satellites, the sensitivities cited here should be close to the lower bound (i.e., most sensitive) figure. Second, the damage threshold value assumes the laser energy passes through the entire optical train and strikes the sensor's focal plane. For lasers tuned sufficiently out of the satellite sensor's detection band, various optical filters, band-selecting beam splitters, and optical coatings would reduce the amount of laser light actually reaching the focal plane. In this case, any sensor damage would likely result from

---

[35] There ample evidence that the Soviet Union considers them to be such. See Paul B. Stares, The Militarization of Space: U.S. Policy, 1945-1984 (Ithaca, NY: Cornell University Press, 1985), p. 165; Johnson, p. 27-28.

laser damage to filters and coatings in the optical train. Because the optical gain affecting optical components in the optical train is much lower than that affecting the focal plane detector material, lower bound sensitivities for out-of-band damage are much higher than 10^{-9} J/cm^2 (fluence) and 10^{-8} W/cm^2 (flux).

Consider the following example. Suppose the entrance aperture of a space-borne optical sensor is 31 cm (c.f., SPOT satellite, Table XI). Assuming the smallest diameter of any relay optics is 3.1 cm, the optical power impinging on any relay optical element is nominally $(31/3.1)^2 = 100$ times that entering the collecting aperture. If the damage threshold for optical coatings is 1.0 J/cm^2, then the effective out-of-band damage threshold for the entire sensor is 0.01 J/cm^2. Consequently, for this simple example the effective out-of-band damage threshold for this sensor is one to two orders of magnitude higher than the fluence levels required for any ground-based imaging technique considered. Therefore, it is still possible to use ground-based laser imaging devices against earth-viewing optical sensor satellites without causing harmful interference.[36]

Table VIII lists various classes of satellites with earth-viewing optical sensors. Associated with each satellite class are typical optical and infrared bands in which they sense. The third and fourth columns list those imaging wavelengths which lie within (conflict with) or lie outside (do not conflict with) the satellite sensing bands. The table suggests that lasers for ground-based laser imaging may be chosen so as not to radiate at wavelengths in the sensitive detection bands of earth-viewing optical satellites. If this is possible, the discussion above suggests that the corresponding damage thresholds for optical satellites at out-of-band wavelengths will be much greater than the in-band thresholds and perhaps higher than the laser illumination figures required for ground-based laser imaging. If suitable lasers outside the

---

[36] This is a very crude calculation. A laser threat assessment for each sensor would have to consider many details of the optical design. For example, the estimate here ignores possible "hot spot" effects of laser light being reflected or refracted onto optical surfaces (onto a field lens, for example).

TABLE VIII

SENSING WAVELENGTHS FOR EARTH-VIEWING OPTICAL SENSORS

SATELLITE TYPE	SATELLITE SENSOR WAVEBANDS (µm)	CONFLICTING LASER WAVELENGTHS (µm)	NON-CONFLICTING LASER WAVELENGTHS (µm)
PHOTORECCE	0.4-0.9[a]	0.589 0.694	1.32 11.2
REMOTE SENSING	0.5-0.9[b] 0.5-1.1[c] 10.4-12.6[d]	0.589 0.694 11.2	1.32
METEOROLOGY	0.5-0.8[e] 8.0-12.5[e] 9.6-18.7[e]	0.589 0.694 11.2	1.32
EARLY WARNING	2.5-4.0[f]	NONE	ALL
AIRCRAFT SURVEILLANCE	4.0-5.0[g]	NONE	ALL

a. Presumed, based on visible bands of Soviet RESURS and OKEAN remote sensing satellites. Nicholas L. Johnson, The Soviet Year in Space 1990 (Colorado Springs, CO: Teledyne Brown Engineering, February 1991), p. 66.

b. Visible band of Soviet RESURS and OKEAN satellites and French SPOT satellite. Johnson, p. 66; Philip N. Slater, Remote Sensing: Optics and Optical Systems (Reading, MA: Addison Wesley, 1980), p. 511.

c. Soviet RESURS and OKEAN satellites. Johnson, p. 66.

d. Soviet RESURS satellites. Johnson, p. 66.

e. Soviet METEOR 2/3 satellites. *Ibid.*, p. 61-62.

f. Presumed, Soviet KOSMOS Launch Detection Satellites.

g. Presumed for future aircraft surveillance spacecraft sensing jet exhaust plumes at 4.2 and 4.4-4.5 micrometers wavelength. Anthony J. LaRocca, "Artificial Sources," William L. Wolfe and George J. Zissis, eds., Infrared Handbook (Washington, DC: GPO, 1978), chapter 2, p. 80.

satellite sensing bands cannot be found (for example, it may be necessary to utilize the 0.589 μm wavelength to operate an adaptive optics system), then other measures must be considered.

A third reason laser imaging of optical satellites may not be precluded is that protective measures designed into the sensor's construction, which may intentionally (or unintentionally) reduce the sensor's vulnerability to laser illuminations, have not been considered. For example, the sensor may possess a protective shutter. Also, since lasers emit at a relatively few, well defined wavelengths, narrowband optical filters may be used to reject (or "block out") undesired optical frequencies. Standard interference filters can be used to reduce the amount of laser light reaching the focal plane.[37] The USAF Wright Laboratory has investigated so-called Rugate filters to protect optical and infrared sensors from laser damage.[38] In theory, these devices can be designed to reflect any number of specified laser wavelengths with high efficiency. Currently, Rugate filters operating in the optical wavelength regime can provide factors of 10^6 rejection of undesired lines while transmitting 95-97 percent of the desired light.[39] According to USAF Wright Laboratory personnel, filter coatings simultaneously reflecting up to six laser lines have been successfully deposited.[40]

Another way satellite operators can protect their space-borne optical sensors is to avoid pointing the sensor in the direction of the illuminating laser. Since high gain optical systems

---

[37] William L. Wolfe, "Optical Materials," William L. Wolfe and George J. Zissis, eds., Infrared Handbook (Washington, DC: GPO, 1978), chapter 7, pp. 104-128.

[38] Rugate filters are specific kind of interference filter whose spectral response is determined by a continuously varying refractive index. The principle advantage of the Rugate filter over more conventional interference filters is the ability to design in an arbitrary number of stop and pass bands without introducing spectral harmonics. Letter from Captain Mary McRae to the author (with attachments), 4 February 1992; telephone conversation with Captain McRae, USAF Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH, 31 January 1992.

[39] Telephone conversation with Captain McRae, 31 January 1992.

[40] *Ibid.*

have restricted fields-of-view,[41] the sensor would have to be pointed within a few degrees of the laser's location to have in-band laser light reach the light-sensitive focal plane.[42] This means that the earth-viewing space sensor will have to be observing the ground in the immediate vicinity of the laser site (with the laser "on") for the focal plane to be illuminated. There is always a risk that out-of-field illumination could cause damage to the optical system, but optical systems are designed to reject out-of field light through the use of stray light baffles.[43] The requirement that the satellite sensor look away in order not be blinded by a ground-based laser could be viewed as unacceptable interference to the satellites normal operations. However, if the spacecraft were not always required to view the earth near the laser site, arrangements could be made to image the satellite on passes where the space sensor was either not operating (e.g., shutter closed) or it was looking elsewhere. Since space sensors have narrow fields-of-view, the elevation angles at which the ground-based laser imager can operate are not severely restricted. For example, if the space sensor were always viewing nadir (toward earth center), a plus or minus two degree field of view would restrict the ground-based laser to operating with elevation angles below 88 degrees. This viewing angle restriction does not significantly reduce the number of opportunities the laser has to image the satellite.

A fourth way laser imaging devices can be operated against optical satellites without causing damage is through a combination of protective and cooperative measures. For example, if the ground-based laser imaging mission were coordinated with the satellite owner,

---

[41] William L. Wolfe, "Imaging Systems," William L. Wolfe and George J. Zissis, eds., Infrared Handbook (Washington, DC: GPO, 1978), chapter 19, pp. 21-23.

[42] The French SPOT sensor, for example, possesses a four degree full angle field-of-view. Michele Chevrel, Michel Courtois and Gilbert Weill, "The SPOT Satellite Remote Sensing Mission," Photogrammetric Engineering and Remote Sensing, vol. 47, August 1981, pp. 1163-1171.

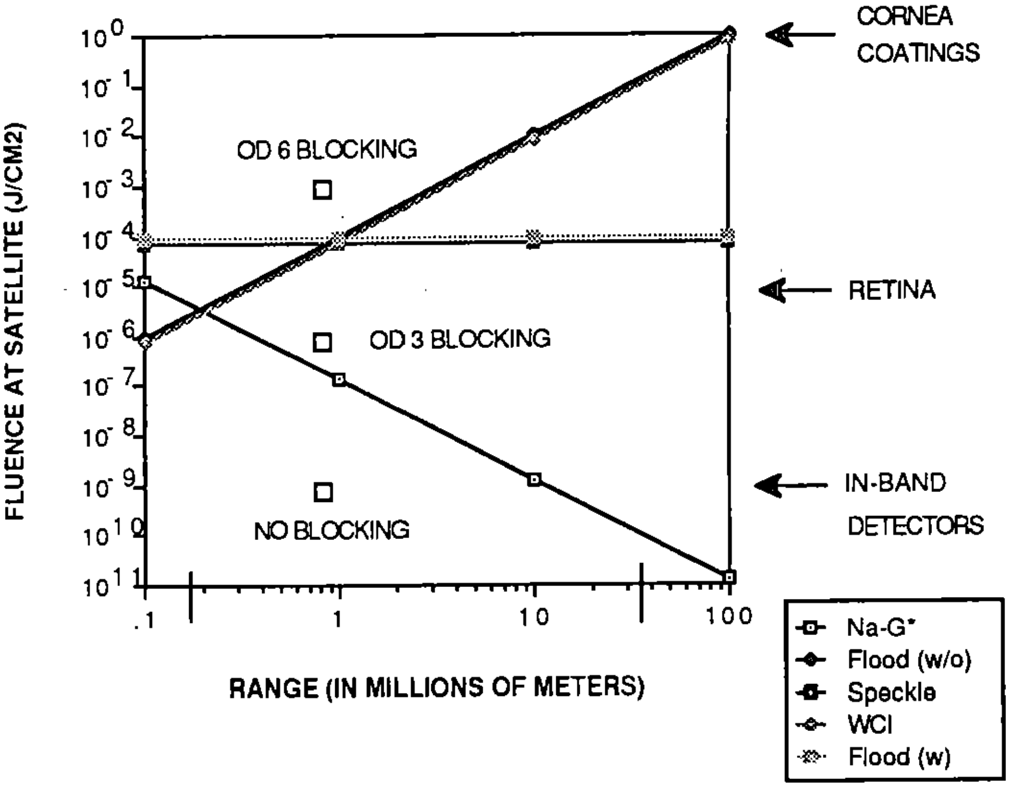
[43] William L. Wolfe, "Imaging Systems," William L. Wolfe and George J. Zissis, eds., Infrared Handbook (Washington, DC: GPO, 1978), chapter 19, pp. 24-25.

the space sensor could be pointed away from the laser during that pass, as suggested above. Second, the satellite owner/operator could request that the laser used to image the satellite operate on a laser wavelength at which the space-borne optical sensor is not sensitive. This being done, the sensor's sensitivity to laser light is raised from an extreme low light sensitivity to one more characteristic of out-of-band damage, as discussed earlier.

Alternatively, satellite owner/operators could design protective measures into their earth-viewing sensors that anticipate the use of lasers from the ground. For example, the French SPOT remote sensing satellites operate at an average orbital altitude of 822 km. If their optical sensors have a damage fluence threshold of 10^{-9} J/cm^2, an optical filter designed to block the sodium laser wavelength of 0.589 μm and having a transmission of only 10^{-3} (optical density OD = 3, corresponding to an optical rejection of 10^3) at this wavelength would enhance the damage sensitivity to 10^{-6} J/cm^2. This damage threshold value is greater (by about a factor of three) than the per pulse fluence a one kilowatt sodium guide star laser deposits on a satellite at this altitude. Figure 6 reproduces the fluence requirements for ground-based laser imaging techniques as a function of altitude (c.f., Figure 4). Superimposed are the damage threshold values for a SPOT satellite with laser band-blocking filters having optical densities of OD 0 (no laser light protection), OD 3 (10^3, rejection), and OD 6 (10^6 rejection). As the figure illustrates, a band-stop filter with optical density of OD 6 would provide a safety margin of more than a factor of 1000 between the expected focal plane fluence from a sodium guide star laser and the sensor's damage threshold. A factor of 10^6 rejection of sodium laser light would also permit a satellite carrying a sensor similar to SPOT's to operate safely during direct guide star laser illumination at any orbital altitude with at least a factor of 100 fluence margin. Similarly, a factor of 10^6 light rejection at the appropriate laser wavelengths would protect optical sensors from direct illumination by all the laser imaging techniques discussed here up to a range of about 3000 km.

FIGURE 6

EFFECT OF BAND-BLOCKING FILTERS ON SENSOR FLUENCE DAMAGE THRESHOLDS



CHAPTER V

PEACETIME RULES OF ENGAGEMENT FOR GROUND-BASED LASER IMAGING SENSORS

Different perceptions of what constitutes laser interference can be used to construct very different laser illumination regimes in space. The guidelines under which the DOD laser sites operate can be described by a set of rules of engagement (ROE). In this chapter we summarize the current peacetime ROE for laser illumination of foreign satellites by DOD sites, and propose three alternative sets of ROE. The current ROE set and these alternatives are distinguished by how "harmful interference" is defined, which class of satellites is being illuminated (and by what laser), and what cooperative measures are introduced to make the regime work. These four sets of ROE are evaluated with respect to the three goals for laser illumination policy identified in chapter III: protection of U.S. space assets, promotion of international cooperation in space, and preservation of future U.S. technology options in space.

In each of the ROE options considered, lasers are prohibited from irradiating satellites at power density levels above one-tenth the equivalent solar flux (or, 0.014 watts per square centimeter)--well below the power level needed to upset the thermal balance of a satellite. As suggested in the previous chapter, this figure should represent a "sure-safe" average power illumination level which would permit continuous, direct illumination of any non-optical satellite for a few minutes. This flux level is, again, more than a factor of ten greater than the power levels needed by the direct illumination imaging systems (flood light, laser speckle, and wideband coherent techniques) to image satellites at ranges of 3000 km or less. One-tenth sol is, however, below the average direct illumination level for a one kilowatt sodium guide star system operating against satellites closer than 250 km (c.f., Figure 5). Since only optical photoreconnaissance satellites are likely to approach such short ranges, other protective measures would have to be taken anyway. Otherwise, techniques for reducing the direct illumination level for laser guide stars (or the other laser imaging techniques for that matter) could be devised. Since all the imaging techniques discussed require only a few seconds to form an image, an added margin of safety is added.

Key aspects of the four laser ROE options considered are summarized in Table IX at the end of the chapter.

CURRENT ROE FOR LASER ILLUMINATION OF FOREIGN SATELLITES

RULES OF LASER ENGAGEMENT

The current set of operating guidelines established for DOD laser illumination of foreign satellites (c.f., chapter 3) follows a conservative interpretation of laser interference. Namely, any intentional illumination of a foreign satellite by a DOD laser site without the owner's permission is considered harmful interference. The essential guidelines are uniformly applied to all satellites, whether they are foreign or domestic. For routine laser site operations, the current U.S. DOD rules of laser engagement against foreign satellites may be summarized:

1. No foreign satellite may be intentionally illuminated by DOD lasers of any power level unless explicit permission is obtained from the owner/operator.

2. To minimize the potential for inadvertent laser illumination, all lasers except those in the "waived" category (i.e., possess beam brightness levels less than 66.7 gigawatts per steradian) must obtain predictive avoidance from the Laser Clearinghouse before receiving USCINCSPACE authorization to radiate into space. Waived lasers are authorized to irradiate into space without prior notification and approval from USCINCSPACE so long as the laser is not pointed at a known foreign satellite.

For the purposes of clarification and comparison to other proposed ROE schemes discussed below, it is important to make note of a few specific points. First, the above guidelines apply to all foreign satellites independent of its national origin or mission. Second, the authority to illuminate any foreign satellite rests entirely with the satellite owner/operator. That is, the laser site must obtain permission from the satellite's owner before USCINCSPACE will authorize laser emission in the direction of the satellite. Third, controls on laser illumination apply to U.S. DOD lasers only (and, currently, voluntary) through the SPADOC Laser Clearinghouse by the authority of USCINCSPACE; non-DOD and non-U.S. lasers are not controlled. Finally, no cooperative measures are currently employed with foreign satellite owner/operators to mitigate the consequences of a possible failure of the U.S. control system.[1]

EVALUATION

The current set of ROE for laser illumination of foreign satellites has contributed to the protection of U.S. space assets. No accidental illuminations of U.S. satellites have been reported in the eight-year history of the Laser Clearinghouse. And, because the LCH effectively limits (through the permission rule) intentional illumination of foreign spacecraft, there is little chance that an accidental illumination of a foreign satellite would evoke a hostile response threatening a U.S. satellite. Through unilateral U.S. action, the current ROE support peaceful international cooperation in space. Adopting a conservative interpretation of what constitutes interference results in procedures which support the provisions of international space law and bilateral agreements preventing interference with national technical means and averting nuclear war. Accidental laser illumination of foreign satellites by DOD lasers has not prompted concern within the international space community.

While these controls on laser emission have not proven to be overly burdensome to laser site operators, the current interpretation of what constitutes interference does limit the applicability of laser sensing of satellites from the ground. This policy and the conservative interpretation of interference from which it stems, it can be argued, restricts the evaluation of new technologies and constrains future applications of laser technology in space. For example,

---

[1] Communications with the satellite owner/operator may be instituted, after the fact, in the course of an investigation or notification of accidental illumination by a DOD laser site. U.S. Department of Defense, U.S. Space Command, Space Defense Operations Center Laser Clearinghouse, USSPACECOM Pamphlet XXX-XX (Draft) (Peterson AFB, CO: 1 January 1988), pp. 4-6.

since the policy does not permit illumination of foreign spacecraft (without permission), the U.S. cannot directly evaluate the capability of ground-based laser sensing techniques against foreign military space threats. A lack of "real world" experience limits the ability to evaluate such techniques relative to other techniques which are not restricted from viewing foreign satellites (e.g., passive optical and radar techniques). The true value of laser sensing can, therefore, not be appreciated nor exploited.

The policy not to illuminate foreign satellites without permission imposes a unilateral restriction on U.S. options. Because of the extreme sensitivity of earth-viewing optical sensors, they are highly vulnerable to blinding by foreign ground-based lasers of a class widely available in the world market.[2] Routine laser operations against foreign satellites would allow the U.S. an opportunity to capitalize on a current strength in U.S. capability, and offer the U.S. ample opportunity to exercise a capability that any determined belligerent might be able to establish.

U.S. abstinence from routine laser illumination of foreign satellites at any power level arguably establishes bad legal precedent. Since international law is largely based on established practice, an arbitrary policy not to illuminate foreign satellites supports the notion that lasers as a whole are harmful, while space surveillance radar (whose use is not even questioned) is not.[3] The current U.S. policy not to illuminate any foreign satellites at the very

---

[2] See discussion on astronomical laser guide stars and mobile laser ranging stations in chapter 2.

[3] Personal and telephone interviews with surveillance radar site operators indicate that surveillance radars may be trained on any satellite unless the satellite owner/operator contacts the radar site for exclusion. This is the opposite of the current policy for laser use, which precludes laser illumination without permission. To date, the Space Shuttle is only satellite the Haystack Long-Range Imaging Radar (X-band, 10 gigahertz operating frequency) has been requested not to illuminate---and, then, only at a time when the Shuttle itself carried an X-band radar which might be jammed by Haystack's radio emissions. Interview with Dr. Raymond Landry, MIT Lincoln Laboratory, Millstone Hill Site, Medford, MA, 3 January 1992; Telephone conversations with Dr. Landry, 23 December 1991; and, Dr Michael Austin, MIT Lincoln Laboratory, Bedford, MA, 23 December 1991. The general policy of allowing radar surveillance of all satellites was confirmed in a telephone conversation with Lieutenant Colonel John Rabins, USAF Space Command (DOJ), Peterson AFB, CO, 6 January 1992.

least slows the application of laser technology to space surveillance and may, by default, result in the loss of future opportunities for these and other applications. The current DOD policy not to use lasers against foreign satellites constrains the future application of this technology, restricting U.S. freedom of action in space.

Under the current ROE, there are three ways to conduct laser tests against foreign satellites. First, the tests could be conducted with the owner's permission. This is an unlikely occurrence at the current time, especially since the laser tests would be conducted by the U.S. military.[4] Even if such tests were permitted, it is likely they would involve obsolete or otherwise "dead" satellites not representative of the current satellite threat class.[5]

Second, the tests could be conducted covertly (that is, tested without the owner's knowledge). Because laser sensing requires active illumination, it may not be possible to conduct an extensive covert test program without being found out (especially if laser warning or other optical sensors are carried on board the target spacecraft). Moreover, the political fallout should covert testing be discovered and brought to light might be unacceptable, perhaps leading to a discontinuation of all future laser tests against foreign spacecraft. Even if covert tests were successfully conducted, the development costs of an operational implementation of such a system (constructed and operated covertly) might not justify the investment without its use in routine operations. And, since the routine use of a laser system cannot be kept covert indefinitely, routine operations of an active system seems to imply its overt use.

---

[4] It has been suggested to the author that if laser operations were performed by an agency other than the DOD, such operations might be less provocative and, therefore, more acceptable to foreign powers.

[5] When the satellites are not designed to operate as laser targets, U.S. satellite owner/operators are reluctant to have their "live" spacecraft illuminated by lasers--especially if they carry earth-viewing optical sensors. Telephone conversations with E. Larry Heacock, Spacecraft Operations Director, National Oceanographic and Atmospheric Administration, 10 January 1992; and Lieutenant Eugene Caudill, USAF Phillips Laboratory, Imaging Technology Branch, 12 December 1991.

The third option, then, is to test and continue to operate laser systems against foreign satellites overtly, but without necessarily seeking explicit permission ahead of time. Here, again, one runs the risk of evoking an undesirable response; and, one must be prepared to live with the possible consequences. It would seem that taking steps to ameliorate these consequences--say, through protection of U.S. space assets, prudent target selection for laser illumination, and the establishment of certain cooperative measures with the satellites' owners--might make this option more acceptable. These considerations provide the foundation for the three ROE options discussed below: conduct operations so as to establish the acceptability of routine laser imaging.

ROE OPTION 1: UNRESTRICTED LASER IMAGING

RULES OF LASER ENGAGEMENT

As a first modification to the current set of laser ROE, one might consider a regime where U.S. laser imaging sensors may operate without any unilateral U.S. restrictions on illuminating foreign spacecraft. This option allows DOD laser sites, subject to the approval of the appropriate authority, to illuminate any satellite it deems necessary--laser illumination is conducted overtly, but without explicit permission from the satellite owner. Justification for this approach lies in an interpretation of the rights of surveillance (Article X of the Outer Space Treaty) and national defense (U.N.Charter) favorable to U.S. interests in space. For the purposes of this discussion, it is assumed that an average laser power density of less than one-tenth of the equivalent solar flux (0.014 watts/cm^2) does not represent a thermal ASAT threat. Because the laser imaging systems considered in this paper radiate average laser powers below about a kilowatt, these systems are not credible thermal-kill ASAT threats to any satellite. In this regime, the ROE for laser illumination are:

1. Any foreign satellite may be illuminated for the purpose of routine surveillance, provided the illuminating laser places an average of less than 0.1 times the equivalent solar flux (0.014 watts/cm^2) on the spacecraft.

2. Any spacecraft owner/operator may seek exclusions from laser illumination if it can justifiably claim such irradiation is harmful to the spacecraft's normal operation.

3. To minimize the potential for inadvertent laser illumination of non-targeted spacecraft, all lasers except those in the "waived" category must obtain predictive avoidance from the Laser Clearinghouse before receiving authorization to illuminate any target satellite.

These guidelines may apply to all satellites independent of their mission and national origin. Target selection for DOD surveillance purposes is determined by USSPACECOM tasking. The authority to illuminate foreign satellites rests with the appropriate authority (say, USCINCSPACE), who views any laser illumination level lower than 0.1 sol not to be a threat to the satellite. The burden of ensuring that such illumination is not harmful lies entirely with the satellite owner/operator, who must protect on-board optical systems from laser illumination if he believes there is a threat. In this regime, laser imaging operations could be conducted against all foreign satellites, unless specifically excepted by mutual agreement with the foreign satellite owner/operator. This situation is analogous to the current procedures followed by space surveillance radar: radar surveillance is assumed to be permitted unless the satellite operator specifically requests not to be illuminated with radar energy.[6] Controls on DOD laser sites is provided through the SPADOC Laser Clearinghouse, as before.

EVALUATION

By opening the door to satellite illumination by DOD laser sites, these ROE remove many of the negative factors associated with the current set of ROE, at the expense of adding several new negatives of its own. By utilizing lasers in surveillance, the U.S. has established a "laser presence," asserting its legal right to surveillance using these techniques. And, routine

---

[6] See comment in footnote 3, this chapter.

laser operations against foreign satellites gives the U.S. military operators the opportunity to build up valuable training with the real space threat while performing the routine peacetime mission of space surveillance, tracking, and imaging. Using lasers for surveillance establishes a legal precedent but unrestricted laser use may, without further consideration, threaten the goal of peaceful international cooperation in space. Positive controls on DOD laser illumination protect U.S. space assets from inadvertent damage, but the illumination of foreign satellites without their explicit permission might be viewed by them as being hostile.

Because of pulsed laser effects, average laser illumination levels significantly below one-tenth sol can be damaging, especially to earth-viewing optical sensors and the eye. Unrestricted laser illumination of Russian photoreconnaissance satellites would likely be viewed as interference with their national technical means of verification, a violation of the ABM Treaty. Similarly, laser illumination (at certain laser wavelengths) of their launch detection satellites would cause interference which could be viewed as militarily provocative, violating the Prevention of Nuclear War agreement. Owner/operators of civil meteorological and optical remote sensing satellites could claim that unrestricted laser illumination of their spacecraft violates the letter of the Outer Space Treaty which bans harmful interference with another nation's "peaceful exploration and use of outer space." If foreign satellite owners sought exclusion from laser illumination, the U.S. might have to prove that such illumination is not harmful or stop operations against those satellites. Other nations might also be disturbed if the U.S. conducted operations against foreign satellites which violated guidelines established for the laser illumination of their own space assets (violating the notion of "equality" established under the Outer Space Treaty). So, in order for the U.S. to rightfully claim that laser illumination was acceptable behavior in the international space community, it would have to first establish it as standard practice with all U.S. spacecraft. While U.S. owner/operators of some non-optical satellites may not have qualms about being irradiated with low levels of laser energy,[7] those carrying earth-viewing optical sensors do have reservations.

A worrisome prospect for U.S. satellite owner/operators (military, civil, and, in the future, commercial) might be an uncontrolled, tit-for-tat response by foreign powers. Here, Russia or third-party powers may choose to respond to the change in U.S. laser illumination policy by illuminating U.S. space assets. Unless these groups derived some tangible benefit from these actions, however, it is hard to see why they would persist in such activity for long. Therefore, if U.S. space systems were sufficiently hardened to prevail under foreign laser illumination, such activity might die off quickly. In any event, it would be advisable to protect U.S. space systems against possible reprisals before an unrestricted U.S. laser illumination policy were introduced.

Initiating the routine and overt use of lasers for satellite imaging may also evoke the development and employment of countermeasures to this capability. The satellite's owner would be expected to respond in a manner consistent with the value of the spacecraft, the perceived credibility of the threat, and the cost of the countermeasure employed. If the countermeasures are passive and protective, such as the use of band-blocking filters or other measures designed to reduce the sensitivity of optical sensors to laser radiation, the response may be stabilizing. Satellite owners might consider operating their spacecraft in higher orbits, but this action will likely compromise the performance of the spacecraft's primary mission. They might also consider trying to actively interfere with the laser sensors operation. Depending on the approach taken, the cost of implementing countermeasures on the next generation spacecraft might not be justified, especially if the laser sensor does not directly

---

[7] As mentioned in chapter 3, the Laser Clearinghouse has, on occasion, permitted U.S. satellites into the laser firing "cone" in order to expand the predictive avoidance windows for some laser tests. Telephone conversation with Lieutenant James Thilenius, U.S. Space Command, Space Control Technical Support Branch (J3SOT), Peterson AFB, CO, 18 February 1992.

threaten the satellite's operation. For example, if a ground-based laser imaging device were known to support to an ASAT weapon, laser illumination of a foreign satellite might imply that some form of ASAT support function (target verification, targeting, etc.) is being exercised. This might be considered threatening, if not harmful, interference even in peacetime. On the other hand, if the laser sensor operates in a surveillance mode and its connections to weapons support are more remote or could be denied (as is the case when an ASAT weapon does not exist), the perception of this imaging laser's threat is much reduced.

ROE OPTION 2: LASER IMAGE NON-OPTICAL SATELLITES ONLY

RULES OF LASER ENGAGEMENT

As a second option, one might consider constraining the laser power to that required for surveillance (well below conventional ASAT standards) as before, but restrict laser operations to non-optical satellites only. As discussed in chapter 4, satellites not carrying earth-viewing optical sensors have both average power and pulse energy damage thresholds several orders of magnitude (factors of 100 to 10,000 for low earth-orbit satellites, c.f. Figures IV and V) above the levels needed for ground-based laser imaging. Therefore, laser imaging operations would not interfere with non-earth viewing optical satellites in low earth orbit. The ROE for this option are

1. Any foreign satellite identified as not carrying earth-viewing optical sensors may be illuminated for the purpose of routine surveillance, provided the illuminating laser places an average of less than 0.1 times the equivalent solar flux (0.014 watts/cm^2) on the spacecraft.

2. Foreign satellites carrying earth viewing optical sensors may not be illuminated under normal circumstances, unless permission is obtained from the spacecraft owner.

3. To minimize the potential for inadvertent laser illumination of non-targeted spacecraft, all lasers except those in the "waived" category must obtain predictive avoidance from the Laser Clearinghouse before receiving authorization to illuminate any target satellite.

This set of ROE makes the assumption that all earth-viewing optical sensors are sensitive to all ground-based laser sensors. This assumption is a simplification of the real situation, since different space sensors have widely varying sensitivities to different laser wavelengths and illumination levels. However, this simplification helps keep the ROE simple. By not illuminating any earth-viewing optical satellite, the U.S. is not required to establish the damage thresholds of these satellites with a high degree of precision. Gathering and verifying vulnerability data on foreign optical satellites may be viewed as intrusive (if not interfering) itself. This regime would protect the sanctity of all optical satellites, permitting earth remote sensing, meteorological, photoreconnaissance, and launch detection satellites to continue to operate without interference from ground-based lasers. As it is, this regime requires the U.S. to determine which satellites carry optical sensors--an issue which, for some space faring nations, may continue to be a source of uncertainty. Furthermore, these guidelines for illuminating foreign satellites are more consistent with current USSPACECOM procedures for illuminating U.S. satellites.

EVALUATION

Restricting laser imaging systems from illuminating known earth-viewing optical satellites should remove many of the most troublesome concerns which arise in the ROE Option 2. Principally, by not permitting laser operations against photoreconnaissance and launch detection satellites, concerns over abrogating the ABM and Prevention of Nuclear War treaties are removed. Concerns over violating more broadly applicable definitions of interference (c.f., Article IX of the Outer Space Treaty) are also largely avoided by not illuminating earth resources and meteorological satellites. Owners of foreign non-optical spacecraft would still have to show cause why their satellites are disrupted by the low levels of laser illumination prescribed by this regime. While Option 1 requires the satellite owners to show cause for all spacecraft (optical and non-optical), Option 2 allows the possibility that low level laser illumination is a threat to earth-viewing optical satellites, and restricts operations accordingly. The satellite threat assessment of chapter 4 suggests it would be very difficult for an owner of a non-optical satellite to claim that spacecraft operations would be interfered with (much less harmed) by a laser in the class used for ground-based laser imaging. The ability for the U.S. to reject such a claim of interference with non-optical satellites would reduce the risk that any nation might consider hostile action in response to the U.S. illuminating their non-optical spacecraft.

As with the first option, the Option 2 regime sets a U.S. precedent for laser illumination of satellites. In the R&D environment, the true capabilities of laser sensing can be assessed against most foreign threat satellites; a positive assessment could then be more easily applied to advocacy for the fielding of operational laser imaging and surveillance sensors. These operational laser sensors would be permitted to operate on a routine basis against foreign, non-optical satellites, thereby providing valuable user training with these techniques. Because non-optical satellites are excluded from such operations, however, specific technology assessments and training against certain high-value military threats (principally photoreconnaissance and meteorological satellites) will not be available. However, with growing experience against low altitude, non-optical satellites, one could presume there would be little additional trouble in applying laser surveillance and weapons principles to military optical satellites when needed.

A principle drawback of this second ROE option concerns the possibility that the foreign satellite owner, not wanting his satellite to be illuminated for any reason, would claim that his spacecraft carried an earth-viewing optical sensor. It is well known, for example, that the U.S. military often "piggybacks" a number of mission packages on its spacecraft busses. A nation interested in protecting its military posture in space from U.S. scrutiny could claim they were doing the same thing. And, while it is generally understood that foreign powers (the former Soviet Union, in particular) do not piggyback currently,[8] this does not rule out the possibility they will change this practice in the future, either in response to U.S. actions to laser illuminate their spacecraft or as a result of economic concerns. However, to demonstrate to the U.S. that low levels of laser illumination were harmful to such a satellite, they would have to divulge the optical capabilities of these systems. Furthermore, it is possible that claims of optical sensors being carried aboard satellites previously presumed to be non-optical could, over time, be verified by other means (radar or passive optical techniques, air and space shows, factory inspections, etc.). And, if foreign powers were intent on piggybacking future generations of spacecraft, arrangements could be made to cooperatively develop protective measures so that these optical sensors could operate under low level laser illumination.

ROE OPTION 3: LASER IMAGE ALL SATELLITES UNDER TAILORED TASKING

RULES OF LASER ENGAGEMENT

Finally, to broaden U.S. opportunities to laser image any foreign satellite, optical or non-optical, one might consider a combination of selectively tasking an array of ground-based laser sensors (operating at different laser wavelengths and operating on different physical principles) together with cooperative measures employed to make foreign satellites less vulnerable to laser illumination. Since only optical satellites are potentially laser-illumination sensitive, these special precautions will only need to be employed for satellites carrying earth-viewing optical sensors. Presumably, such protective measures and precautions are in the owners' interests anyway, owing to the world-wide proliferation of laser technology and the growing use of laser radiation into space. Indeed, such protective measures could be "spun off" from current developments to laser harden U.S. satellites. The viability of this approach

---

[8] Stares, Space and National Security (Washington, DC: The Brookings Institution, 1987), p. 15.

could be demonstrated by first introducing these measures in U.S. military, civil, and commercial optical satellites. The ROE for Option 3 are

> 1. Any foreign satellite identified as not carrying earth-viewing optical sensors may be illuminated for the purpose of routine surveillance, provided the illuminating laser places an average of less than 0.1 times the equivalent solar flux (0.014 watts/cm^2) on the spacecraft.
>
> 2. Foreign satellites carrying earth-viewing optical sensors may be illuminated subject to illumination conditions worked out with the spacecraft owner. For example, ground-based lasers will be tasked based on their operating wavelengths, on-target flux requirements, and the understood damage thresholds for potential target satellites.
>
> 3. To minimize the potential for inadvertent laser illumination of non-targeted spacecraft, all lasers except those in the "waived" category must obtain predictive avoidance from the Laser Clearinghouse before receiving authorization to illuminate any target satellite.

The approach in this set of ROE is to maximize U.S. laser sensing opportunities while reducing the provocation foreign satellite owners might feel by being laser illuminated by the U.S. military. The ROE under Option 3 provide an expansion of laser imaging coverage beyond that of Option 2 and, subject to acceptable arrangements with the foreign satellite owners, may provide coverage of all satellite classes. The major difference between the provisions of this option and those of Options 1 and 2 is that the decision to illuminate foreign satellites (especially, foreign optical satellites) follows the establishment of mutual agreements covering the illumination conditions. This arrangement further reduces the risk that foreign satellite owners will be provoked to take action against U.S. interests in space or elsewhere.

Under this third option, the U.S. agrees to place operational controls on the lasers it uses to image foreign satellites. If the target satellite carries an earth-viewing optical system, the U.S. agrees to illuminate with a laser system which will not threaten the target spacecraft. This can be done by selecting a laser wavelength which does not pass the optical system and whose on-target flux and fluence levels are below mutually agreed-upon acceptable thresholds. For example, since earth-viewing sensors often shun sensing in the 1.1 to 2.5 micrometers wavelength band, ground-based imaging lasers operating at 1.3 microns, say, would be permitted provided the on-satellite fluence level is below a level which would cause out-of-band damage to optics and optical coatings. Similarly, a wideband coherent laser imaging system operating at 11.2 micrometers wavelength would not normally be a threat to low earth orbit, earth-viewing sensors which sense in the visible and near infrared wavelength bands. These sensors would, however, be restricted from illuminating meteorological satellites which conduct temperature soundings in the 8.0 to 12.5 micron band. On the other hand, owners of spacecraft which sense in the visible may, in any event, want to protect their sensitive spaceborne sensors from laser radiation emitted by astronomers employing laser guide stars.[9] If such protective measures were employed aboard earth-viewing optical satellites (e.g., remote sensing, meteorological, and military photoreconnaissance satellites), the use of laser guide star techniques for military surveillance would also be greatly facilitated. Satellites which were protected from guide star laser illumination, however, would not necessarily be protected from other laser imaging sensors operating at other wavelengths. Therefore, the use of these lasers would need to be restricted by mutual agreement.

EVALUATION

Extending U.S. sensing opportunities to include all foreign satellites allows it to assess the capabilities of laser sensing technologies against all possible foreign space threats. The legal precedent for laser sensing is established, with a host of new sensing techniques available to exercise the right of use. From an R&D standpoint, this regime offers the greatest opportunities to evaluate new laser sensor technologies. The military services and intelligence community have the widest selection of techniques from which to choose operational systems.

---

[9] This situation would present an interesting turnabout of a more familiar arrangement. Astronomers have successfully lobbied to have civil authorities install sodium vapor street lamps to reduce the extent to which night time light pollution interferes with the operation of ground based optical observatories. The astronomers then employ optical filters to block out the narrow emission lines of these lamps.

For those systems deployed, this regime provides a wide latitude for routine operational exercises and training.

Implementing a cooperative regime will take time and place some additional burdens on the spacecraft owners. However, it is in the satellite owners interests to protect their systems from inadvertent damage from lasers. Cooperative involvement with the space powers strengthens the mutual protection of earth resources and meteorological satellites (and, with regard to the former Soviet Union, national technical means of verification and launch detection satellites), both through the cooperative employment of satellite protective measures and through the development of mutually agreed upon procedures (rules of the road) for laser illumination. Given a potential future rise in space laser traffic, it is in everyone's best interest to reach understandings to deal with this trend while establishing procedures to avoid accidental and unintentional military confrontation. Some solutions could leverage currently on-going technology developments, the Rugate filter work being done to support sensor survivability, for example. In the interest of establishing laser illumination regimes with increased international security and crisis stability, sharing U.S. technology in this area might be justified.

With regard to the broader issue of weapons in space, international agreements which accept low power laser illumination of satellites as standard practice will help widen the distinction between laser ASAT weapons and the peaceful uses of lasers in space. That is, if optical sensors were protected from laser illumination by any factor, this would raise the required power level needed to harm satellites by that amount. This, in turn, could greatly reduce number of lasers capable of doing damage and could make the task of verifying any future ASAT arms agreements that much easier.[10] The use of laser imaging for surveillance is

---

[10] A recent analysis of technical requirements for laser ASAT treaty verification is reported in Ronald H. Ruby, "Laser ASAT Test Verification." A Study Group Report to the Federation of American Scientists (n.p.: February 1991).

consistent with U.S. space policy goals which include the pursuit of national security objectives. And, even though tracking and imaging with lasers may be used to support military functions such as determining space order of battle and conducting ASAT targeting drills, the routine use of lasers for surveillance does not represent a hostile act in and of itself. The employment of modest protective measures, whether physical (as in narrowband filters which block certain laser wavelengths) or procedural, will further widen this distinction leading to a heightened sense of mutual security in space.

TABLE IX

PRINCIPAL FEATURES OF FOUR ROE OPTIONS

ROE OPTION	APPLICABLE SATELLITE CLASS	AUTHORIZATION TO ILLUMINATE PROVIDED BY	ILLUMINATION THRESHOLD	COOPERATIVE MEASURES EMPLOYED
CURRENT ROE	ALL	SATELLITE O/O	PER ARRANGEMENT WITH O/O	NONE
OPTION 1	ALL	USCINCSPACE	< 0.1 SOL AVERAGE IRRADIANCE	NONE
OPTION 2	NON-OPTICAL SATELLITES	USCINCSPACE	< 0.1 SOL AVERAGE IRRADIANCE	NONE
	OPTICAL SATELLITES	SATELLITE O/O	PER ARRANGEMENT WITH O/O	NONE
OPTION 3	NON-OPTICAL SATELLITES	USCINCSPACE	< 0.1 SOL AVERAGE IRRADIANCE	NONE
	OPTICAL SATELLITES	USCINCSPACE	SATELLITE SPECIFIC	TAILORED LASER TASKING SATELLITE PROTECTIVE MEASURES EMPLOYED

Source: See text.

CHAPTER VI

CONCLUSIONS

Ground-based laser imaging techniques are on the threshold of revolutionizing space surveillance and imaging. A number of laser imaging concepts currently under investigation within the DOD promise to improve the capability to image space objects in low earth orbit with spatial resolutions of 10 centimeters (four inches) or better--almost two orders of magnitude better and under a wider set of operating conditions than current, passive optical techniques. However, even though these techniques can be tested against cooperative U.S. spacecraft, an assessment of their true utility as military surveillance assets is being hampered by the current DOD policy not to permit routine laser illumination of foreign satellites.

The current policy not to illuminate foreign spacecraft originated during the early 1970s so that inadvertent (or, even intentional) laser illumination would not upset the verification regime then being established for the ABM Treaty and subsequent bilateral agreements on strategic arms limitation and reduction. The non-illumination policy is also justified in the interests of upholding the sovereign rights of nations operating spacecraft and in the interests of building confidence against an inadvertent outbreak of nuclear war. Upon a detailed study of these factors, however, one finds that laser illumination of satellites is not specifically prohibited and even those actions which could cause "harmful interference" are left open to broad interpretation. The USSPACECOM has established procedures for controlling emissions of laser radiation from DOD laser sites into space so that inadvertent damage to U.S. and foreign satellites can be prevented. Currently, these procedures--while apparently effective in preventing accidental illumination by DOD laser sites--apply to only to DOD sites, which follow these procedures voluntarily. According to USSPACECOM, harmful interference amounts to *any* intentional laser illumination of a foreign satellite by a DOD site.

A detailed technical assessment of satellite vulnerabilities to laser radiation demonstrates that laser imaging techniques are not harmful to satellites which do not carry earth-viewing optical sensors (here, referred to as non-optical satellites). The required single-pulse laser energy density deposited on satellites being imaged at ranges less than 6000 km is five to six orders of magnitude below that needed to produce skin ruptures in aluminum. And, even operating at high pulse repetition rates needed to drive high bandwidth adaptive optics or to perform image data averaging, the average deposited laser power needed to image satellites up to 15,000 km is less than the total optical power deposited by the sun. At satellite ranges of 3000 km or less, the flood light (without adaptive optics), laser speckle, and wideband coherent imaging techniques deposit less than one-tenth of an equivalent solar constant of flux. A one kilowatt sodium laser guide star system and the flood light imager (with guide star-aided adaptive optics) exceed this flux level only for satellites at ranges less than 250 km. Since ground-based laser sensors only need to illuminate a satellite for a few seconds (at most) to form a high resolution image, laser imaging devices should not pose a thermal upset threat to any low earth orbit satellite. Geometrical viewing restrictions prevent laser illumination from interfering with earth limb (horizon) sensors and other optical sensors which would normally be carried on board for spacecraft stabilization purposes.

While ground-based laser imaging systems are not a damage threat to non-optical satellites, almost all laser systems are potentially threatening to some earth-viewing optical sensors. Analysis which considers the performance characteristics of current-technology earth remote sensing optical sensors suggests that the single pulse energy for any of the ground-based laser imaging systems is at least two, and perhaps as much as six, orders of magnitude above the damage threshold for low earth orbit optical satellites. Since laser damage to an optical sensor requires--in addition to a damaging light intensity level--an optical co-alignment of the receiver with the laser beam and wavelength matching, a number of unilateral and cooperative protective measures to avert inadvertent sensor damage from laser imaging can be suggested. The use of spectral band-blocking filters, for example, can reduce the laser intensity at the sensor's focal plane by several orders of magnitude. Selecting the stop band to correspond to the wavelength of ground-based lasers could be used to protect earth-viewing sensors from inadvertent laser illumination (e.g., from civil or military lasers not tracking the satellite) and even intentional illumination from ground-based laser imaging devices. The possibility that spaceborne earth-viewing sensors could be protected from direct laser illumination suggests that some ground-based laser imaging techniques could be safely applied to all satellites.

Because the extent to which laser illumination causes "harmful interference" depends on the nature of the ground-based laser device used and the satellite being imaged, a number of different laser illumination regimes can be constructed. The current set of operating rules and three alternatives were considered in this study. Under the current set of rules administered by the USSPACECOM Laser Clearinghouse, harmful interference is prevented and inadvertent illumination is minimized by prohibiting direct laser illumination of any satellite unless explicit permission is obtained from the satellite's owner/operator. Unfortunately, this policy effectively prevents the evaluation of laser imaging techniques against foreign satellites, greatly limiting their application in operational military systems. Further, this policy establishes a negative precedent which may constrain future military applications of laser technology in space.

The consideration of three alternative regimes which would allow overt laser illumination for imaging purposes points up the need for some tacit or explicit cooperation between the DOD, who wishes to exercise its right to space surveillance using lasers, and the satellite operators, who have a right to unimpeded operation of their space systems. For the case of non-optical satellites, very little cooperation is needed. Because laser illumination at the levels required for satellite imaging are not damaging to these spacecraft, the simple assurance (or, knowledge) that no earth-viewing optical sensor is carried aboard should suffice to permit laser illumination. If, however, a satellite to be imaged carries an earth-viewing optical sensor--or, the satellite's owner claims it is carrying one (and this claim cannot be refuted with confidence)--exercising the right to image the satellite with a laser threatens to violate the satellite's right to normal operations. This quandary, and the risks associated with breaking from a two decades long DOD policy not to illuminate foreign satellites, leads to the following fundamental conclusion:

Even though ground-based laser imaging techniques may provide demonstrative benefits to the U.S. military posture in space, they cannot be routinely applied so long as they pose an in-band sensor damage threat to earth-viewing satellite optical systems. So, in order to apply laser imaging to routine satellite surveillance, steps must be taken to reduce the vulnerability of earth-viewing optical sensors to a level acceptable to the satellite owner/operator.

One way to reduce the threat of damage to earth-viewing optical sensors is through protective and/or cooperative measures. Possible cooperative, protective measures include the selection of agreed-upon laser sensing wavelengths, the use of band-stop filters to reject certain laser lines, and the scheduling of laser imaging when an earth-viewing sensor is turned away or capped. An obvious benefit of such measures is that they would help mitigate the negative fallout should the United States initiate laser imaging operations against a foreign satellite without seeking explicit permission from its owner. The use of protective measures may naturally arise out of the interests of foreign satellite owners' to protect their investments in space, just as it would be in the U.S. interest, from the proliferation of ground-based scientific, civil, and military lasers.

If satellite protective measures were applied widely enough, then, it is possible that an operational niche for ground-based laser imaging could develop. From the U.S. military perspective, such a opening would permit the exploitation of laser sensing for routine space surveillance, intelligence, and weapons support functions. From a military and civil perspective, ground-based laser imaging could be used for high resolution on-orbit inspection and troubleshooting. Implementation of protective measures and procedures would also serve to widen the physical distinctions between real laser antisatellite weapons and peaceful applications of lasers in space.

APPENDIX

IN-BAND SENSOR DAMAGE CONSIDERATIONS FOR GROUND-BASED LASER IMAGERS

Thresholds for in-band sensor damage are determined by establishing the laser fluence damage thresholds for the photosensitive detector materials, measured at the detector surface, and then applying the front-end optical gain introduced by the optical system.

Detector Damage Thresholds

Table X summarizes the damage thresholds of popular (but, unhardened) optical and infrared detector materials to irradiation by the lasers considered for ground-based satellite imaging sensing from earth (c.f., chapter 4). The threshold damage figures are calculated from data compiled by Bartoli et. al.[1] The table lists the laser illuminator being considered, its wavelength, and the laser pulse length for the sensing application being considered. Damage thresholds are listed for Bartoli's detector materials sensitive to the nearest laser wavelength. (The wavelength in parenthesis under the detector material type indicates the wavelength at which the damage studies were conducted.)

The damage thresholds given in the last two columns of the table were calculated from Bartoli's damage threshold irradiance values, plotted in Figure 1 of their paper. The values for damage threshold fluence in the next to last column represent the total energy density applied by a single, short pulse (pulse length given in the third column). Bartoli's data indicate that the detector materials studied are damaged by a constant amount of laser energy when the length of the pulse ranges from 10^{-7} (the shortest pulse length they studied) to 10^{-3} seconds. The threshold fluence values listed in the next to last column indicate the range of pulse energies

---

[1] F. Bartoli, et al., "Irreversible Laser Damage in IR Detector Materials," Applied Optics, vol. 16, November 1977, pp. 2934-2937.

TABLE X

SENSOR DAMAGE THRESHOLDS

LASER	WAVEL (μM)	PULSE LENGTH[a]	DETECTOR MATERIAL[b] (WAVEL.)	DAMAGE FLUENCE[b] (J/CM^2)	DAMAGE IRRADIANCE[a] (W/CM^2)
SODIUM	0.589	69 μs	Si-PIN (0.69 μm)	100	10^4
RUBY	0.694	1 ms	Si-PIN (0.69 μm)	100	10^4
IODINE	1.315	10 μs	PbS/PbSe (1.06 μm)	5	150
			Si-PIN (1.06 μm)	200	10^4
CO_2	11.17	30 μs	TGS (10.6 μm)	9	50
			MCT-PC (10.6μm)	240	10^3

a. See text, chapter 2.

b. F. Bartoli, et al., "Irreversible Laser Damage in IR Detector Materials," Applied Optics, vol. 16, November 1977, pp. 2934-2937.

needed to damage these different detector materials when irradiated with different wavelengths of laser light.

For laser irradiation times longer than about 0.1 second, Bartoli's data indicates that significant amounts of absorbed laser energy will be re-radiated or conducted from the detector surface, increasing the total laser energy needed to inflict damage. In this time regime, a nearly constant laser power must be applied to damage the detector surface so that these losses are overcome. This constant laser irradiance (in general, different for each wavelength and detector material) is listed in the far right column.

These figures for detector damage thresholds should be taken only as order-of-magnitude estimates, however. While damage threshold for specific detector samples can be determined fairly accurately, an insufficient number of detector samples were tested to determine the variability between samples from a given manufacturer, much less the variability between different manufacturers. It is suggested that a safety factor of ten should be applied to account for spread in the detector damage data obtained, but detectors manufactured by different sources could be outside this range.[2]

The Bartoli data and these considerations lead us to conclude that a lower bound damage irradiance for these detector materials considered (across all laser wavelengths) is about 5 J/cm^2 at the operating pulse lengths of these systems. Lower-bound damage threshold irradiances for a train of pulses or continuous wave laser operation is about 50 W/cm^2 or less. Finally, we note that, depending on the laser wavelength and the detector material chosen, the variability in the detector damage thresholds is about two to three orders of magnitude.

Front-End Optical Gain

For light which originates at point or a laser a far distance from the entrance aperture, the lens focuses the collected light onto a small spot in the focal plane. A perfect optical system with no aberrations produces a diffraction spot on the order of λ x (f-number) in size, or about 3.5 microns for an f/3.5 optic at a wavelength of one micrometer. Owing to the conservation of energy, the fore optics will concentrate all the laser light collected by the system (minus the fraction lost to absorption or scattering) onto this small spot. The peak light intensity at the focal spot I_f is related to the light intensity at the sensor's entrance aperture I_{INC} according to

---

[2] Telephone conversation with Dr. Koto White, USAF Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH, 9 January 1992.

$$I_f = I_{INC}\, G_O \tag{A.1}$$

where

$$G_O = \frac{D^2}{\lambda^2}\,(f/no.)^{-2} \tag{A.2}$$

is the optical gain of the imaging system. Note that the peak focal plane irradiance is proportional to the square of the aperture size and inversely to the square of the wavelength and f-number. Because the wavelength of optical and infrared radiation is so short, sensors usually possess extremely large optical gains; and, consequently have a high potential for in-band laser damage.

Table XI gives estimated optical gains for five representative, high-gain satellite optical systems based on their published values for aperture size D and f-number (or, focal length, since f-number = f/D). Nominal peak optical gains are listed in column 5 according to equation (A.2). The optical gains are computed at a wavelength in the center of their operating band, indicated in the second column, which is close to one of the ground-based sensing laser lines (c.f., Table VI).

The Hubble Space Telescope (HST), launched from the Space Shuttle in June 1990, is NASA's largest aperture orbiting optical observatory with an aperture of 2.4 meters.[3] Although it is not intended to be pointed earthward, it provides a useful example of the large optical gains achievable with large optical imaging systems. The HST f/24 focus position provides an optical gain of 3.3×10^{10} at 0.55 micrometers wavelength.

The French Systeme Probatoire de la Terre (SPOT) spacecraft was designed as an earth remote sensing and imaging satellite.[4] Although its collecting aperture is about one eightieth the area of the Hubble, its fast f/3.5 optics provide a comparable optical gain of 2.6×10^{10}.

---

[3] Daniel J. Schroeder, Astronomical Optics (New York: Academic Press, 1987), p. 213.

[4] Michele Chevrel, Michel Courtois, and Gilbert Weill, "The SPOT Satellite Remote Sensing Mission," Photogrammetric Engineering and Remote Sensing, vol. 47, August 1981, pp. 1163-1171.

SPOT's f/3.5 prescription was selected to provide a relatively wide field-of-view (approximately 4 degrees full angle) and to match the focal plane spot size to the detector cells of its charge-coupled device linear detector sensing array. While this is not the largest (or fastest) optical system one could conceive, it does point out the extremely large gain possible in today's spaceborne optical systems. The fact that even larger aperture or faster optics could be put into orbital operation suggests that even more sensitive systems are possible. For example, if SPOT's telescope system were replaced with an f/3.5 optic the size of the Hubble's (2.4 meters), this system's optical gain would exceed 10^{12}.

Sensor Damage Threshold

The last two columns of Table XI list damage threshold fluence (energy) and irradiance (power) values calculated by dividing the sensor damage threshold values contained in corresponding columns of Table X by the peak optical gain for the satellite sensor system [c.f., equation (A.1)]. These figures suggest that a minimum damage threshold for pulsed lasers is in the range of 10^{-9} J/cm^2, while the minimum threshold irradiance is about 10^{-8} W/cm^2.

TABLE XI

OPTICAL GAINS AND EQUIVALENT SENSOR DAMAGE THRESHOLDS

SATELLITE (SENSOR)	WAVEBAND (μM)	APERTURE DIAMETER (METERS)	F/NO	MAXIMUM OPTICAL GAIN[e]	MINIMUM DAMAGE FLUENCE (J/CM^2)[e]	MINIMUM DAMAGE IRRADIANCE (W/CM^2)[e]
LANDSAT (TM BAND 2)[a]	0.52-0.60	0.41	F/5.6	1.7E+10	5.9E-9	5.9E-7
LANDSAT (MSS BAND 7)[b]	0.8-1.1	0.23	F/3.6	4.5E+9	1.1E-9	3.3E-8
LANDSAT (TM BAND 6)[a]	10.4-12.5	0.41	F/5.6	4.1E+7	2.2E-7	1.2E-6
SPOT[c]	0.50-0.59	0.31	F/3.5	2.6E+10	3.8E-9	5.9E-7
HUBBLE[d]	0.55	2.4	F/24	3.3E+10	3.0E-9	3.0E-7

a. Philip N. Slater, Remote Sensing: Optics and Optical Systems (Reading, MA: Addison-Wesley, 1980), pp. 500-507.

b. *Ibid.*, pp. 473-484.

c. Michele Chevrel, Michel Courtois, and Gilbert Weill, "The SPOT Satellite Remote Sensing Mission," Photogrammetric Engineering and Remote Sensing, vol. 47, August 1981, pp. 1163-1171.

d. Daniel J. Schroeder, Astronomical Optics (New York: Academic Press, 1987), p. 213.

e. Computed values, see text.

BIBLIOGRAPHY

Ackerman, Robert K. "Laser Radar Discriminates Against Decoy Targets." Signal, June 1990, pp. 41-42.

Adelman, Kenneth. "Why Verification is More Difficult (and Less Important)." International Security, Spring 1990, pp. 141-146.

Telephone Conversation with Major John Anderson, U.S. Air Force Phillips Laboratory, Starfire Optical Range, Kirtland AFB, NM. 6 January 1992.

Arnett, E.H. "Antisatellite Weapons Issue Paper." AAAS Program on Science, Arms Control, and National Security, AAAS Publication No. 90-115, January 1990.

Telephone Conversation with Dr. Michael Austin, MIT Lincoln Laboratory, Bedford, MA. 23 December 1991.

AVCO Everett Research Laboratory. AMOS Users Manual. Puunene, Maui, HI: 1982.

Baker, David. Shape of Wars to Come. New York: Stein and Day, 1984.

Barnaby, Frank. Space Weapons. New York: Gallery Books, 1984.

Bartoli, F., Esterowitz, L., Kruer, M., and Allen, R. "Irreversible Laser Damage in IR Detector Materials." Applied Optics, Vol. 16, November 1977, pp. 2934-2937.

Belsher, J.F. and Fried, D.L. "Shear Speckle Imaging." SPIE Proceedings, Vol 1351, 1990, pp. 604-615.

Benko, Marietta et al. Space Law in the United Nations. Boston: Martinus Nijhoff Publishers, 1985.

Rettig P. Benedict, "Space Object Identification Challenges and Opportunities," Unpublished Briefing. Albuquerque, NM: W.J. Schafer Associates, Inc., 22 April 1991.

Berkowitz, Marc J. "Anti-Satellites and Strategic Stability." Airpower Journal, Vol. 3, no. 4, Winter 1989, pp. 46-59.

Bishop, Gary M. "A Capability in Search of a Policy: The Offensive Use of Lasers." Unpublished Student Paper. Department of Operations, U.S. Naval War College, Newport, RI. 23 February 1990.

Blacker, Coit D. and Duffy, Gloria Duffy, eds. International Arms Control Issues and Agreements. Stanford University Press, 1984.

Blair, Bruce G. Strategic Command and Control: Redefining the Nuclear Threat. Washington, D.C.: The Brookings Institution, 1985.

Blechman, Barry M. ed., Technology and the Limitation of International Conflict. Washington, D.C.: Foreign Policy Institute, School of Advanced International Studies, The Johns Hopkins University Press, 1989.

Bloembergen, N. and Patel, C.K.N., co-chairs, "Report to the American Physical Society of the Study Group on Science and Technology of Directed Energy Weapons." Reviews of Modern Physics, Vol. 59, no. 3, July 1987, pp. S1-S202.

Bridges, W.B. et al. Space Object Imaging Techniques, Final Technical Report Under Contract DAAH01-73-C-0629. Malibu, CA: Hughes Research Laboratories, June 1974.

Browne, Malcome W. "Anti-Missile Technology Delights Astronomers." The New York Times, 6 August 1991, pp. C1, C9.

Burke, William J. and Sagalyn, Rita C. "Active Space Experiments Affect Treaty Obligations." Signal, Vol. 44, no. 10, June 1990, pp. 73-75.

Burrows, William E. Deep Black: Space Espionage and National Security. New York: Random House, 1986.

Callaham, M. and Tsipis, K. High Energy Laser Weapons: A Technical Assessment. Program in Science and Technology for International Security Report No. 6. Cambridge MA: Massachusetts Institute of Technology, Department of Physics, 1980.

Canan, James W. War in Space. New York: Berkley, 1984.

Carter, Ashton B. "The Current and Future Military Uses of Space." Joseph S. Nye and James A. Shear, eds., Seeking Stability in Space. Lanham, MD: University Press of America, 1987.

Carter, Ashton B. "Satellites and Anti-Satellites: The Limits of the Possible." International Security, Spring 1986, pp. 46-98.

Carter, Ashton B. Directed Energy Missile Defense. Washington, D.C.: Government Printing Office, 1984.

Telephone Conversation with Lieutenant Eugene Caudill, U.S. Air Force Phillips Laboratory, Imaging Technology Branch. 12 December 1991.

Interview with Colonel Robby Chadbourne, The Joint Chiefs of Staff, J5 (Space Policy), The Pentagon, Washington, DC. 18 December 1991.

Charschan, S.S., ed., Lasers in Industry. New York: Van Nostrand Reinhold Company, 1972.

Chayes, Antonia Handler and Doty, Paul, eds., Defending Deterrence: Managing the ABM Treaty Regime Into the Twenty First Century. Washington, D.C.: Pergamon-Brassey's International Defense Publishers, 1989.

Chevrel, Michele, et al. "The SPOT Satellite Remote Sensing Mission." Photogrammetric Engineering and Remote Sensing, Vol. 47, no. 8, August 1981, pp. 1163-1171.

Christol, Carl Q. The Modern International Law of Outer Space. New York: Pergamon Press, 1982.

Clark, Theresa R. "Rules of Engagement for Space Warfare 1990-2000", Unpublished Student Paper. Department of Operations, U.S. Naval War College, Newport, RI: 23 February 1990.

Cochran, Curtis D., et al. Space Handbook. Maxwell AFB, AL: Air University Press, January 1985.

Collins, Graham P. "Making Stars See Stars: DOD Adaptive Optics Work is Declassified." Physics Today, Vol. 45, February 1992, pp. 17-21.

Collins, John M. Military Space Forces: The Next 50 Years. Congressional Research Service Report 89-578 RCO. Washington, DC: The Library of Congress, 12 October 1991.

Cooke, Claude, et al. "Ranging, Communications, and Simulation Systems." W.L. Wolfe and G.J. Zissis, eds., The Infrared Handbook. Washington, D.C.: Government Printing Office, 1978.

Davis, Richard, W. and Mitchell, Douglas J. "On the Utility of Antisatellite Weapons," Unpublished Note, U.S. Air Force Phillips Laboratory, Kirtland Air Force Base, NM, June 1981.

Degnan, John J. "Applications of Laser Ranging to Ocean, Ice, and Land Topography." SPIE Proceedings, Vol. 1492, 1991, pp. 176-186.

Degnan, John J. "An Overview of NASA SLR Stations and Their Performance." presented at the Seventh International Workshop in Laser Ranging Instrumentation, Matera, Italy, October 1989.

Degnan, John J. "Satellite Laser Ranging: Current Status and Future Prospects." IEEE Trans in Geoscience and Remote Sensing, GE-23, July 1985, pp. 398-413.

Telephone Conversation with Dr. John J. Degnan, Director, Crustal Dynamics Program, NASA Goddard Space Flight Center, 6 January 1992.

Donabedian, Martin. "Cooling Systems." Chapter 15. W.L. Wolfe and G.J. Zissis, eds., The Infrared Handbook. Washington, D.C.: Government Printing Office, 1978.

Durch, William J. Antisatellite Weapons, Arms Control Options, and the Military Use of Space. Cambridge, MA: President and Follows of Harvard College, 1984.

Durch, William J., ed., National Interests and the Military Use of Space. Cambridge, MA: Ballinger Publishing Co., 1984.

Interview with Dr. Brian E. Edwards, MIT Lincoln Laboratory, Lexington, MA, 3 January 1992.

Farley, Philip J., "Arms Control and US Soviet Security Cooperation." in US-Soviet Security Cooperation. Alexander L. George, Philip J. Farley, and Alexander Dallin, eds., New York: Oxford University Press, 1988.

Fetter, Steve, "Protecting Our Military Space Systems." Edmund S. Muskie, ed. The U.S. in Space. Washington, DC: Center for National Policy Press, 1988.

"Firefly Laser Experiment Successful in Measuring Inflatable Decoy Motion." Aviation Week and Space Technology, 23 April 1990, p. 75.

Fugate, R.Q., et. al. "Measurement of Atmospheric Wavefront Distortion Using Scattered Light From a Laser Guide-Star." Nature, Vol. 353, 12 September 1991, pp. 144-146.

Gaddis, John Lewis. "The Evolution of a Reconnaissance Satellite Regime." in US-Soviet Security Cooperation. Alexander L. George, Philip J. Farley, and Alexander Dallin, eds., New York: Oxford University Press, 1988.

Gardner, Chester S. "Sodium Resonance Fluorescence Lidar Applications in Atmospheric Science and Astronomy." Proceedings of the IEEE, Vol. 77, March 1989, pp. 408-418.

Gardner, Chester S., et al. "Sodium Laser Guide Star Technique for Adaptive Imaging in Astronomy." SPIE Proceedings, Vol. 1114, March 1989.

Garthoff, Raymond L. "Detente and Confrontation: American-Soviet Relations from Nixon to Reagan." Washington, D.C.: The Brookings Institution, 1985.

Garwin, Richard L. "The Soviet Response: New Missiles and Countermeasures." J. Tirman, ed., Empty Promise - The Growing Case Against Star Wars, Boston: Beacon Press, 1986.

Garwin, Richard L., et al. "Antisatellite Weapons." Scientific American, Vol. 250, June 1984, pp. 45-55.

Garwin, Richard L. and Jarvis, Theodore, Jr. "Non-ABM Technologies." Antonia Handler Chayes and Paul Doty, eds., Defending Deterrence. New York: Pergamon-Brassey's, 1989.

Gatland, Kenneth. The Illustrated Encyclopedia of Space Technology. New York: Harmony Books, 1981.

Giffen, Robert B. US Space System Survivability: Strategic Alternatives for the 1990s. Washington, D.C.: National Defense University Press, 1982.

Goodman, J.W. et al. "Experiments in Long Distance Holographic Imagery." Applied Optics, Vol. 8, 1969, pp. 1481-1486.

Gottfried, Kurt and Blair, Bruce G., eds., Crisis Stability and Nuclear War. New York: Oxford University Press, 1985.

Gray, Colin S. "Does Verification Really Matter? Facing Political Facts About Arms Control Non-Compliance." Strategic Review, Vol 18, no. 2, Spring 1990, pp. 32-42.

Greenwood, Ted. Reconnaissance, Surveillance and Arms Control. London: International Institute for Strategic Studies, 1972.

Hackett, James T. and Range, Robin. "Proliferating Satellites Drive US ASAT Need." Signal, Vol 44, no. 9, May 1990, pp. 155-156.

Hafner, Donald L. "Negotiating Restraints on Anti-Satellite Weapons: Options and Impact.", J.S. Nye and J.A. Shear, eds., Seeking Stability in Space, Lanham, MD: University Press of America, 1987.

Hardy, J.W. "Adaptive Optics: A New Technology for the Control of Light." Proceedings of the IEEE, Vol. 66, 1978, p. 651.

Hayes, Bradd C. "Naval Rules of Engagement: Management Tools for Crisis." RAND Note N-2963-CC. Santa Monica, CA: The RAND Corporation, July 1989.

Telephone Conversation with E. Larry Heacock, Spacecraft Operations Director, National Oceanographic and Atmospheric Administration. 10 January 1992.

Hurwitz, Bruce A. The Legality of Space Militarization. New York: North Holland, 1986.

Telephone Conversation with John Hussey, Director, Landsat and Meteorological Satellite Development, National Oceanographic and Atmospheric Administration. 2 December 1991.

Idell, Paul S., J.R. Fienup, and R.S. Goodman. "Image Synthesis From Nonimaged Laser-Speckle Patterns." Optics Letters, Vol. 12, 1987, pp. 858-860.

Idell, Paul S. and Gonglewski, John D. "image Synthesis from Wavefront Measurements of a Coherent Diffraction Field." Optics Letters, Vol. 15, 1990, pp. 1309-1311.

Idell, Paul S. and Voelz, David G. "Nonconventional Laser Imaging Using Sampled-Aperture Receivers." Optics and Photonics News, April 1992, pp. 8-15 (to appear).

Jasani, Bhupendra M. Outer Space - Battlefield of the Future? London: Taylor and Francis, Ltd., 1978.

Jasani, Bhupendra M., ed., Outer Space - A New Dimension of the Arms Race, Cambridge, MA: Oelgeschlager, Gunn, and Hain, 1982.

Jasani, Bhupendra and Barnaby, Frank. Verification Technologies: The Case for Surveillance by Consent. London: Berg Publishers for the Centre for International Peacebuilding, 1984.

Jasani, Bhupendra and Sakata, Toshibumi, eds., Satellites for Arms Control and Crisis Monitoring, New York: Oxford University Press, 1987.

Jelen, George, F. "Space Systems Vulnerabilities and Counter Measures." William J. Durch, ed., National Interests and the Military Use of Space, Cambridge, MA: Ballinger, 1984.

Johnson, Nicholas L. Soviet Military Strategy in Space. London, New York: Jane's Publishing Inc., 1987.

Johnson, Nicholas L. Soviet Space Programs, 1980-1985. San Diego, CA: Univelt, 1987.

Johnson, Nicholas L. The Soviet Year in Space, 1986. Colorado Springs, CO: Teledyne-Brown Engineering, 1987.

Johnson, Nicholas L. The Soviet Year in Space, 1990. Colorado Springs, CO: Teledyne-Brown Engineering, 1991.

Telephone Conversation with Dr. William E. Keicher, Laser Radar Measurements Group, MIT Lincoln Laboratory, Lexington, MA. 19 December 1991.

Interview with Dr. William.E. Keicher, Laser Radar Measurements Group,MIT Lincoln Laboratory, Lexington, MA: 3 January 1992.

Keicher, William.E., et al. "The Firepond Long Range Imaging CO_2 Laser Radar." Optical Society of America Conference on Coherent Laser Radar, Snowmass, CO, 8-12 July 1991.

Kennedy, William V. Intelligence Warfare: Today's Advanced Technology Conflict. New York: Crescent Books, 1983.

Klass, Phillip J. "Anti-Satellite Laser Use Suspected." Aviation Week and Space Technology, 8 December 1975, pp. 12-13.

Kutyna, Donald J. "We Lead Today, But What About Tomorrow?" Defense 91, July - August 1991, pp. 20-29.

Labrie, Roger P., ed. "ABM Treaty, Article XII." SALT Hand Book: Key Documents and Issues 1972-1979. Washington, D.C.: American Enterprise Institute for Public Policy Research, 1979.

Interview with Dr. Raymond Landry, MIT Lincoln Laboratory, Millstone Hill Site, Westford, MA: 3 January 1992.

Telephone Conversation with Dr. Raymond Landry, MIT Lincoln Laboratory, Millstone Hill Site, Westford, MA. 23 December 1991.

LaRocca, Anthony J. "Artificial Sources." W.L. Wolfe and G.J. Zissis, eds., Infrared Handbook, Washington, D.C.: Government Printing Office, 1978.

"Laser to Create Star, Assist Astronomers." The Newport (RI) Daily News, 27 January 1992, p. A5.

Lee, Christopher. War in Space. London: H. Hamilton, 1986.

Lippay, Victor G. "Laser Astronomy: An International Affair." Photonics Spectra, May 1989, pp. 138-148.

"Livermore Laser Advances Draw New Funding for Continued Research." Aviation Week and Space Technology, 17 February 1992, p. 42.

Luongo, Kenneth N. and Wander, W. Thomas, eds. The Search for Security in Space. Ithaca: Cornell University Press, 1989.

Lupton, David. On Space Warfare: A Space Power Doctrine. Maxwell AFB, AL: Air University Press, 1988.

Lynn-Jones, Sean M. "A Quiet Success for Arms Control." International Security, Vol. 9, no. 4, Spring 1985, pp. 154-184.

Telephone Conversation with Captain Mary McRae, U.S. Air Force Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH. 31 January 1992.

Letter (with attachments) from Captain Mary McRae, U.S. Air Force Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH to the Author. 4 February 1992.

MacGregor, Charles H. and Livingston, Lee H. Space Handbook, eleventh revision, Maxwell AFB, AL: Air University Press, 1977.

Macvey, John W. Space Weapons, Space War. New York: Stein and Day, 1979.

Mano, Jack. Arming the Heavens: The Hidden Military Agenda for Space, 1945-1955. New York: Dodd, Mead and Co., 1984.

Martin, B. et al. "The New Ground-Based Optical Telescopes." Physics Today, Vol. 44, March 1991, pp. 22-30.

Massie, N.A., et al. "Low-Cost, High-Resolution, Single-Structure Array Telescopes for Imaging Low-Earth-Orbit Satellites." Applied Optics, Vol. 31, 1 February 92, pp. 447-456.

Massie, N.A., et al. "Stalking Satellites in High Resolution." Lasers and Optronics, Vol. 9, June 1990, pp. 45-50.

Memorandum for the Joint Chiefs of Staff, "Proposed DOD Directive on Prevention and Reporting Laser Damage to Space Assets." Acting Deputy Director, Defense Research and Engineering (Test and Evaluation), 18 August 1989.

Memorandum for Secretary of Army, Secretary of the Navy, Secretary of the Air Force, and Director, Advanced Research Projects Agency. "Irradiation of Aircraft and Satellites by Lasers." Director of Defense Research and Engineering, 24 July 1970. FOR OFFICIAL USE ONLY.

Memorandum from U.S. Air Force Space Command (JA) to U.S. Air Force Space Command (IN), "Space Treaty Questions," 24 Jul 89.

Miller, Barry. "New Roles Grow for Electro-Optics." Aviation Week and Space Technology, 22 June 1970, pp. 155-156.

Telephone Conversation with Lieutenant Colonel Robert Miller, The Joint Chiefs of Staff, J36 (Space), The Pentagon, Washington, DC. 5 December 1991.

Interview with Lieutenant Colonel Robert Miller, The Joint Chiefs of Staff, J36 (Space), The Pentagon, Washington, DC. 18 December 1991.

Morrison, David C. "An Uncertain Hour for Laser Weapons." Lasers and Optronics, Vol. 9, June 1990, p. 6.

National Academy of Sciences. Restoration of Atmospherically Degraded Images. Washington, D.C.: 1966.

Telephone Conversation with Mr. Harold Newby, U.S. Air Force Phillips Laboratory, Malabar Test Site, FL. 27 November 1991.

Ogorkiewicz, R.M. "Eye-Safe Neodymium Lasers." International Defense Review, Vol. 23, no. 2, February 1990, pp. 174-175.

Pace, Scott. Assessing Options for Anti-Satellite Arms Control: the Analytic Hierarchy Process. Santa Monica, CA: Rand Corporation, 1986, p. 21.

Payne, Keith B., ed., Laser Weapons in Space: Policy and Doctrine. Boulder, CO: Westview Press, 1983.

Telephone Conversation with William Peacock, Deputy Program Manager, Meteorological Satellites, NASA-Goddard Space Flight Center. 3 December 1991.

Peebles, Curtis. Guardians: Strategic Reconnaissance Satellites. Novato, CA: Presidio Press, 1987.

Perroots, Leonard H. "Soviet Beam Weapons Are Near Tactical Maturity." Signal, Vol. 44, no. 7, March 1990, pp. 37-39.

Piotrowski, John L. "Challenge in Space: A Joint Effort." U.S. War Institute Proceedings, Vol. 116, no. 2, February 1990, pp. 32-36.

Piotrowski, John L. "Why the US Needs an Antisatellite." National Defense, Vol. 74, no. 455, February 1990, pp. 36-39.

Power, John W. "Space Control in the Post-Cold War Era." Airpower Journal, Vol. 4, no. 4, Winter 1990, pp. 24-33.

Telephone Conversations with Lieutenant Colonel John Rabins, U.S. Air Force Space Command (DOJ), Peterson AFB, CO. 6 January 1992 and 20 February 1992.

RCA Corporation. Electro-Optics Handbook, Technical Series EOH-11. Lancaster, PA: RCA Corporation, 1974.

Reynolds, Glenn H. and Merges, Robert P. Outer Space: Problems of Law and Policy. San Francisco: Westview Press, 1989.

Rowell, William F. Arms Control Verification: A Guide to Policy Issues for the 1980s. Cambridge, MA: Ballinger Publishing Co., 1986.

Ruby, Ronald H. et al. Laser ASAT Test Verification. A study group report to the Federation of American Scientists, 20 February 1991.

Sagan, Scott D. "Reducing the Risks: A New Agenda for Military-to-Military Talks." Arms Control Today, Vol. 21, no. 6, July/August 1991, pp. 16-21.

Saleh, Bahaa E.A. and Teich, Malvin Carl. Fundamentals of Photonics. New York: John Wiley & Sons, Inc., 1991.

Schott, John R. "Remote Sensing of the Earth: A Synoptic View." Physics Today, Vol. 42, no. 9, September 1989, pp. 72-79.

Schroeder, Daniel J. Astronomical Optics. New York: Academic Press, 1987.

Scrivener, David and Sheehan, Michael. Bibliography of Arms Control and Verification, Aldershot, Hants, England: Dartmouth Publishing Co., 1990.

Sepp, G. "Earth Laser Beacon Sensor for Earth Oriented Geosynchronous Satellites." Applied Optics, Vol. 14, no. 7, July 1975, p. 1719.

Sica, Louis. "Estimator and Signal-to-Noise Ratio for an Integrative Synthetic Aperture Imaging Technique." Applied Optics, Vol. 30, 1991, pp. 206-213.

Siegman, Anthony, E. Lasers. Mill Valley, CA: University Science Books, 1986.

Simonette, D.S. "The Development and Principles of Remote Sensing." Robert N. Colwell, ed., Manual of Remote Sensing, Vol. 1, Falls Church, VA: American Society of Photogrammetry, 1983.

Slater, Philip N. Remote Sensing: Optics and Optical Systems. Reading, MA: Addison-Wesley Publishing Company, 1980.

Smith, Marcia S. ASATs: Antisatellite Weapons Systems. Congressional Research Service Issue Brief, Order Code IB85176. Washington, D.C.: The Library of Congress, 11 December 1991.

Smullin, Louis D. and Fiocco, Giorgio. "Optical Echoes from the Moon." Nature, Vol. 194, 30 June 1962, p. 1287.

Stares, Paul B. The Militarization of Space: U.S. Policy, 1945-1984. Ithaca, NY: Cornell University Press, 1985.

Stares, Paul B. Space and National Security. Washington, D.C.: The Brookings Institution, 1987.

Stares, Paul B. "Rules of the Road for Space Operations." Barry M. Blechman, ed., Technology and the Limitation of International Conflict, Washington, D.C.: The Johns Hopkins Foreign Policy Institute, 1989.

Steinberg, Gerald M. Satellite Reconnaissance: The Role of Informal Bargaining. New York: Praeger Publishers, 1983.

Telephone Conversation with Lieutenant Colonel David Stone, U.S. Air Force Phillips Laboratory, Imaging Technology Branch, Kirtland AFB, NM. 20 February 1992.

Suits, Gwynn H. "Natural Sources." W.L. Wolfe and G.J. Zissis, eds., The Infrared Handbook. Washington, D.C.: Government Printing Office, 1978.

Sullivan, Leo J. "Infrared Coherent Radar." SPIE Proceedings, Vol. 227, 1980, pp. 148-161.

Telephone Conversation with Dr. Leo J. Sullivan, Laser Radar Measurements Group, MIT Lincoln Laboratory, Lexington, MA. 20 December 1990.

Tebo, Albert. "Adaptive Optics: The Promise for High Resolution Ground-Based Astronomy." OE Reports, Vol. 96, December 1991.

Telephone Conversations with Lieutenant James Thilenius, USN, U.S. Space Command, Space Control Operations Technical Support Branch, Peterson AFB, CO. 5 and 19 December 1991, 10 January 1991, and 18 February 1992.

Thompson, Laird A. and Gardner, Chester S. "Excimer Laser Guide Star Techniques for Adaptive Imaging in Astronomy." SPIE Proceedings, Vol. 1114, March 1989.

Thompson, Laird A. and Gardner, Chester S. "Experiments on Laser Guide Stars at Mauna Kea Observatory for Adaptive Imaging in Astronomy." Nature, Vol. 328, 1987, pp. 229-231.

Thompson, Leslie. "Remote Sensing Using Solid-State Array Technology." Photogrammetric Engineering and Remote Sensing, Vol. 45, January 1979, pp. 47-55.

Tsipis, Kosta, et al., eds. Arms Control Verification: The Technology That Made It Possible. Washington, D.C.: Pergamon-Brassey's International Defense Publishers, 1986.

Tucker, Compton J. "A Comparison of Satellite Sensor Bands for Vegetation Monitoring." Photogrammetric Engineering and Remote Sensing, Vol. 44, November 1978, pp. 1369-1380.

Tyson, R.K. Principles of Adaptive Optical Systems. San Diego, CA: Academic Press, 1991.

U.S. Air Force. Air Force Basic Doctrine Assignment of Responsibilities for Development of Aerospace Doctrine AFR 1-2, 10 September 1990.

U.S. Air Force. Air Force Operational Doctrine: Space Operations (draft) AFM 2-25, 6 June 1990,

U.S. Air Force. Basic Aerospace Doctrine of the United States Air Force (draft) AFM 1-1, 24 June 1991.

U.S.Air Force Phillips Laboratory. "Starfire Optical Range." PL/LTE Fact Sheet, 1991.

U.S. Air Force Phillips Laboratory Commander. "Letter Change No. 2 to the Air Force Maui Optical Station (AMOS) Security Classification Guide, 9 August 1989." 22 July 1991.

U.S. Congress, House, House Conference Report to Accompany H.R. 2100. National Defense Authorization Act for Fiscal Years 1992 and 1993, Report 102-311. Washington, D.C.: Government Printing Office, 13 November 1991.

U.S. Congress, Senate, Department of Defense Appropriations for Fiscal 1975. "Basic Principles of Negotiations on Future Limitation of Strategic Offensive Weapons." Washington, D.C.: Government Printing Office, 1975, p. 61, paragraph 4.

U.S. Department of Defense, "Department of Defense Space Policy," Memorandum for Correspondents, March 10, 1987.

U.S. Department of Defense. *Soviet Military Power*. Washington, D.C.: Government Printing Office, 1986.

U.S. Department of Defense, U.S. Space Command, *Doctrine for Space Control Forces*, USSPACECOM Pamphlet 2-1, 27 March 1990.

U.S. Department of Defense, U.S. Space Command, *Space Defense Operations Center Laser Clearinghouse*. USSPACECOM Pamphlet XXX-XX (Draft). Peterson AFB, CO: 1 January 1988.

U.S. President, "U.S. Space Policy." Washington, D.C.: The White House, Office of the Press Secretary, 16 November 1989.

U.S. Treaties, etc. "Agreement Between the Government of the United States of America and the Government of the Union of Soviet Socialist Republics on the Prevention of Dangerous Military Activities." Signed 12 June 1989.

Vance, Cyrus R. "Compliance with the SALT I Agreement." Roger P. Labrie, ed., *SALT Handbook: Key Documents and Issues: 1972-1979*. Washington, D.C.: American Enterprise Institute for Public Policy Research, 1979.

Walker, J.L. "Range Doppler Imaging of Rotating Objects." *IEEE Transactions*, Vol. AES-16, January 1980, pp. 23-52.

Weber, Steven and Drell, Sydney. "Attempts to Regulate Military Activities in Space." in *US-Soviet Security Cooperation*. Alexander L. George, Philip J. Farley, and Alexander Dallin, eds., New York: Oxford University Press, 1988.

Welsh, Byron M. et al. "Effects of Nonlinear Resonant Absorption on Sodium Laser Guidestars." *SPIE Proceedings*, Vol. 1114, March 1989.

Telephone Conversation with Dr. Koto White, U.S. Air Force Wright Laboratory, Hardened Materials Branch, Wright-Patterson AFB, OH. 6 January 1992.

Wilkening, Dean A. "Space-Based Weapons." William J. Durch, ed., *National Interests and the Military Use of Space*. Cambridge, MA: Ballinger, 1984.

Wolf, James R. "Toward Operational-Level Doctrine for Space - A Progress Report." *Airpower Journal*, Vol. 5, no. 2, Summer 1991, pp. 28-40.

Wolfe, William L. "Imaging Systems." Chapter 19. W.L. Wolfe and G.J. Zissis, eds., *The Infrared Handbook*. Washington, D.C.: Government Printing Office, 1978.

Wolfe, William L. "Optical Materials." Chapter 7. W.L. Wolfe and G.J. Zissis, eds., *The Infrared Handbook*. Washington, D.C.: Government Printing Office, 1978.

Interview with Colonel Peter Worden, Director, Technology Directorate, Space Defense Initiative Organization (SDIO/TN), U.S. Naval War College, Newport, RI. 15 December 1991.

Wright, Ralph. "Sensor Implications of High-Altitude Low Contrast Imaging." Photogrammetric Engineering and Remote Sensing, Vol. 45, January 79, pp. 63-66.

DATE 29 Oct 91

From: Major Paul S. Idell, USAF, CNC&S
(Rank) (Name) (Service) (CNW or CNC&S)

To: President, Naval War College
Via: (1) Director, Advanced Research Program
(2) Advanced Research Council
(3) Deputy to the President

Subj: REQUEST TO PERFORM ADVANCED RESEARCH PROJECT IN LIEU OF CORE CURRICULUM DURING WINTER TRIMESTER
(~~Fall,~~ Winter, ~~Spring~~)

Ref: (a) NAVWARCOLINST 3920.1B

Encl: (1) Application for Designation as Advanced Research Associate

1. In accordance with reference (a), I request permission to conduct an Advanced Research Project during the WINTER trimester in lieu of participating in the core curriculum during that period. Enclosure (1) describes my proposed project and outlines my qualifications to accomplish such an undertaking.

2. If this request is approved, I understand that I will be designated an Advanced Research Associate and be administratively assigned to the Advanced Research Program while engaged in my project. Despite the full-time nature of this one-trimester withdrawal from the core curriculum to pursue a rigorous research commitment, I understand that I am still required to take an elective and meet all JPME requirements. During the period of my research, I will participate in special Naval War College events to the same extent as other students remaining in the core curriculum.

3. If selected for the student Advanced Research Associate Program, I recognize that I will be expected to complete a substantial project report or research contribution of professional quality, in final smooth form, in the time allotted.

Paul Idell
(Signature of Applicant)

CENTER FOR NAVAL WARFARE STUDIES
ADVANCED RESEARCH PROGRAMS

ADVANCED RESEARCH ASSOCIATE APPLICATION

29 Oct 91	92-04W
(Date of Application)	**ARP Control No. (Leave Blank)**

NOTE FOR STUDENT APPLICANT: Please complete this application by typing (or neat printing), attach the formatted forwarding letter and return to ARP.

A. NAME IDELL, Paul S. Major, USAF, CNC&S
(Last) (First) (Middle Init) (Rank) (Svc) (Coll)
2806 [redacted] TOP SECRET/SCI (SBI, 30 May 91)
(Desig/MOS) (SSN) (Security Clearance/Date Granted)

B. ADDRESS [redacted]
(Number and Street) (City and State) (Zip)

C. TELEPHONE [redacted] CUBE # 3020
(Student Station #)

D. TITLE/TOPIC OF PROPOSED PROJECT Space Policy for Laser Illumination of Foreign satellites

(Attach to this form a 2-3 page descriptive summary of your planned research undertaking to include clear, concise statements of subject, purpose, scope, methodology, anticipated data sources, nature of product, audience for whom writing, possible applications of your work, and expected security classification) → Atch 1

E. CHARACTER/STYLE OF PROPOSED RESEARCH
Research to be performed during Fall, Winter, Spring trimester (circle one) and will be individual/Group (circle one) project.
(If group project, all members of proposed group shall submit individual applications as a package).

F. FINANCIAL SUPPORT (Please estimate costs):
Travel $ 1800 **Per Diem $** 700 **Total $** 2500

Trips to (No. of days) Albuq NM (3), Wash, DC (2), Co.Spr. CO (2), ( )

G. EDUCATION (List all military/civilian undergraduate and graduate schools attended, major courses of study, and degrees awarded, in reverse chronological order):

DATES	INSTITUTION	MAJOR	DEGREE
8/82 - 9/86	Stanford University	Electrical Engr.	Ph.D.
7/77 - 12/78	Air Force Inst. Tech.	" "	M.S.E.E.
8/73 - 5/77	Lehigh University	" "	B.S. E.E.

H. EXPERIENCE/BACKGROUND (List all significant duty assignments for past six years in reverse chronological order):

DATES	ORGANIZATION	LOCATION	NATURE OF DUTIES
1/86–7/91	USAF Phillips Lab,	Kirtland AFB, NM,	Research manager and Branch Chief
8/82–12/85	Stanford University,	Stanford, CA	Ph.D. Student

I. ACADEMIC/SCIENTIFIC HONORS AND PROFESSIONAL SOCIETY MEMBERSHIPS:

Fellow, SPIE (International Optical Engineering Society); member, IEEE, Optical Society of America, Tau Beta Pi, Eta Kappa Nu

3. RECORD OF AUTHORSHIP/PUBLISHING

DATE **TITLE/DESCRIPTION** **INSTITUTION/PUBLISHER**

Author (or Co-author) of 19 professional publications and 12 professional conference papers (see lists & resume' attached, Atch 2)

K. PRELIMINARY LIAISON (It is recommended that you consult with others prior to submitting this research application-if you have done so describe the extend of liaison beyond internal NWC discussion.)

I have coordinated this proposal with USAF Phillips Laboratory, where the focus of laser research exists within the Air Force. I have also begun discussions with OSD-Space Policy and US Space Command for support.

L. FACULTY ADVISOR(S) (All Advanced Research Associates must have one or more faculty advisors for their projects. Advisors may be chosen from the teaching departments and/or the Center for Naval Warfare Studies. Since part of the faculty advisor's responsibility is assisting in defining the terms of reference and scope of the project, it is necessary to acquire at least one faculty advisor prior to submitting this application. In addition, by signing on as a faculty advisor, the faculty advisor agrees to offer guidance, review your work, and provide written comments and a recommended grade for inclusion in ARP's overall appraisal of your final research project.):

FACULTY ADVISOR'S NAME	DEPT.	SIGNATURE OF ADVISOR
STEPHEN O. FOUGHT	NSDM	

ADVANCED RESEARCH ASSOCIATE APPLICATION

Summary of Proposed Research

Title: "Space Policy for Laser Illumination of Foreign Spacecraft"

Researcher: Major Paul S. Idell, USAF, CNC&S

Background: Current U.S. Space Command policy prohibits laser illumination of foreign satellites, despite the fact there is no international agreement expressly forbidding it. In large part, this policy (originally laid down in 1970) arises from the operator's desire to avoid any action which might be perceived as interference with verification measures protected by the 1972 US-USSR Anti-Ballistic Missile (ABM) Treaty.

It is my view (call it my "working thesis" at this point) that the current, unilateral DoD policy which prohibits laser illumination of foreign satellites is too simplistic and overly constraining. Recent advances in laser technology and instrumentation offer a number of significant benefits to U.S. military activities in space were this technology made more widely available to space operators. In sum, the current laser illumination policy unnecessarily limits the flexibility of our current forces to respond to current and projected future threats in space.

Purpose: The purpose of this research is to develop the essential elements of a U.S. space policy which would guarantee our right to exercise the use of lasers against foreign spacecraft without unnecessarily upsetting the intended positive and/or stabilizing aspects which are in the U.S. national and defense interest.

Scope: As I see it, it may be possible to develop a range of policy options which, at different levels perceived threat and hostility, can exploit the advantages of laser illumination technology (perhaps at different levels of fluence or under different levels of operational control or restriction) to enhance our military effectiveness against foreign space systems. To ensure that proper controls are adhered to and unintended provocation is averted, it may, for example, be advantageous to pursue a policy which includes bilateral or multi-lateral international agreements to regulate the use of lasers in space. The salient elements of such agreements would be explored in my study.

Any proposal to widen the use of lasers in space must consider a number of overriding technical/policy issues. The

Atch 1

first is that of interfering with national technical means of verification protected by the ABM Treaty, mentioned in the background paragraph. A second is the current controversy surrounding the U.S. moratorium on the testing of anti-satellite (ASAT) weapons. As an integral part of my study, I will explore the prospects for and the consequences of expanded use and tests of lasers against targets in space within the context of these, and other, policy concerns. (A more complete list of these concerns will be presented in a paper I am completing this trimester under the Directed Research (DR) elective.)

Methodology and Sources: Initially, I will conduct a thorough review and analysis of factors affecting the current laser illumination policy. This review will include an examination of historical justifications for the Space Command policy and a review of pertinent aspects of space law. Next, I will develop the case that laser illumination provides compelling technical and operational benefits to U.S. space activities. In this assessment I will make use of my own technical expertise, literature sources, and that of the directed energy group at the USAF Phillips Laboratory.

Guided by my initial review and analysis, I will develop a set of draft policy options for an expanded application of laser illumination in space. I will prepare a policy white paper on this subject, which I will review with the appropriate offices in Washington (principally OSD and Joint Space Offices). Following this "calibration step," I will adjust and expand the policy options, clarifying the discussion and exploring the upside and downside consequences of the proposed policy options.

I am, as a part of my DR project, assembling a list of background documentation on this subject (including authoritative documents and sources of testimony and interviews).

Nature of the Product: In addition to the knowledge I will have gained in completing this study, I anticipate two principal written products. First, I will prepare written report documenting the historical background, analysis, and policy recommendations made. This will be the product I submit for the course grade. Additionally, I will provide the recommended text for a policy memorandum to be issued/coordinated by OSD. It is my hope that OSD would, on seeing the advantages of the policy options I propose, work to coordinate and enact them.

Intended Audience: There are three main groups who will find the results of my study useful. First, there are the policy makers in OSD and the DCI. There is currently intense interest in the issue of laser ASAT testing which falls squarely in the scope of my study. Additionally, these groups will benefit from a thorough examination of the technology/policy tradeoffs associated with the use of lasers in space which are at the core of my research. Second, the space operators (USSPACECOM, AFSPACECOM) will benefit as the study will help them think more broadly about the applications of lasers in space, perhaps influencing future operational requirements for expanded and more flexible space operations. Thirdly, the research and development community (OSD, US Army Strategic Defense Command, SDIO, Air Force Space Division, and Navy SPAWAR) will benefit from a better appreciation of how new laser technology--and new space policy--can be adapted support military space operations.

Possible Applications of Work: See above discussion.

Expected Security Classification: Work on this study will be conducted up through Top Secret/SCI. I anticipate that the bulk of the report can be written at the Secret level, with perhaps a Top Secret/SCI annex.

Date Prepared: 30 October 1991

PAUL STEVEN IDELL

Major, USAF
DOR: 1 August 1988
AFSC: 2806 (2825)

[redacted]

Assignment Availability: July 1992 (Following ISS)

Old Duty Address (until 25 Jul 91):
PL/LMS
Kirtland AFB, NM 87117-6008
(505)846-4405/AV 246-4405

Duty Address (after 5 Aug 91):
Naval War College Student, USAF
Newport, RI 02841-5010
(401) 841-3373 /AV 948-3373

Home Address (after 1 Aug 91):
[redacted]

SERVICE HISTORY:

Feb 91 – Present	*Chief, Advanced Imaging Concepts Branch*, Phillips Laboratory (formerly Air Force Weapons Laboratory), Kirtland AFB, NM. Responsible for developing and executing a new laboratory research thrust to provide advanced, high resolution optical imaging sensors for airborne and space sensing platforms. Supervises 16 senior civilian and Air Force scientists and engineers. Coordinates and advocates research program internally within the Phillips Lab and externally with user/sponsor organizations. Responsible for comprehensive technical and management assessments of AMOS and Malabar test sites, and a long-term development plan for Phillips Lab optical test sites.
Jan 86 – Jan 91	*Advanced Imaging Technology Program Manager*, Phillips Laboratory. Program manager and principal scientific investigator for an Air Force special access program to evaluate high-payoff electro-optical approaches for satellite acquisition, tracking, and imaging. Managed a $5.0 million annual research budget. Assembled, trained, and directed a 14-person, in-house government research team. Managed about 20 contracted R&D efforts. Consulted for other classified programs and on various DoD technical review panels.
Aug 82 - Dec 85	*Doctoral student*, Department of Electrical Engineering, Stanford University, Stanford, CA. Emphasis on optical coherence theory, Fourier and statistical optics, and digital image/signal processing. Thesis: "Optimal Imaging Concentrators" applied coherence theory to finding the best way to focus partially coherent light onto a target or targets.
Jan 79 - Jul 82	*Electro-Optics Project Officer*. Rome Air Development Center, Griffiss AFB, NY. Managed various Air Force and DARPA sponsored research contracts including: mosaic focal plane array sensor development, ARPA Maui Optical Station (AMOS), and ASAT targeting from airborne satellite trackers.
Jul 77 - Dec 78	*Masters Student*, Electrical Engineering (Electro-optics). Air Force Institute of Technology, Wright-Patterson AFB, OH. Emphasis in optical communication and countermeasures.

EDUCATION:

Civilian:	Ph.D. Electrical Engineering, Stanford University (1986). M.S. Electrical Engineering, Air Force Institute of Technology (1978). B.S. Electrical Engineering, Lehigh University (1977).
PME:	SOS -- in residence (1981). ISS -- to attend Naval College of Command and Staff, Naval War College, Newport, RI reporting 12 Aug 91.

Atch 2

SIGNIFICANT CAREER ACCOMPLISHMENTS/AWARDS:

1977 Distinguished graduate, Air Force ROTC, Lehigh University.

1978 Distinguished graduate, AFIT M.S. Program.

1982 Selected for AFIT Senior Commanders Program which sponsored my Ph.D. degree program at Stanford. Also, selected for Air Staff Training (ASTRA), which I declined.

1982 Air Force Commendation Medal

1987 Awarded Air Force Weapons Laboratory 1987 Giller Award in recognition of the AFWL's top technical achievement of that year, for the invention, demonstration, and evaluation of a new laser-imaging technique.

1991 Initiator and principal investigator of a field test which produced the highest-resolution image of any orbiting space object ever obtained from the earth's surface. Experiment team won the 1990 Air Force Science and Engineering Award, Category II (Advanced Technology and Systems Concepts).

PROFESSIONAL/TECHNICAL AFFILIATIONS:

- Fellow of the SPIE; Member, Optical Society of America and the IEEE.
- Chairman, SPIE Conference on Digital Image Recovery and Synthesis, San Diego, CA, August 1987.
- Chairman, SPIE Conference on Digital Image Synthesis and Inverse Optics (with A. Gmitro and I. LaHaie) 9-13 July 1990.
- Chairman, Modern Imaging session at the 19th, 20th, and 21st Snowbird Winter Colloquia on Quantum Electronics, Snowbird UT, January 1989, 1990, and 1991, respectively.
- Technical Program Committee, OSA/IEEE Topical Meeting on Signal Recovery and Synthesis, April 1992.

Published or presented over 30 technical papers in professional journals/conferences.

OTHER ACCOMPLISHMENTS:

1984 Co-authored and edited a 400 page Stanford University engineering department report entitled "AGSAT: A Space-Based Remote Sensing Service for Crop Management." Report documents the design of a four-spacecraft satellite constellation for optical remote sensing and assessment of agricultural fields.

1989 Weapons Laboratory nominee and finalist for 1989 USAF Basic Research Award (not selected) for original research pertaining to the characterization and evaluation optical images corrupted by laser-speckle noise.

1991 Elected Fellow of the Society of Photo-Optical Instrumentation Engineers (SPIE).

PERSONAL:

35 years old. Excellent health. Married to Cynthia Fukuda Idell with one son, 10 months old. Outside interests include carpentry/home remodeling, playing soccer (which I do in the Albuquerque Men's Soccer League), reading and writing technical journal articles.

(All information current as of 10 Jul 91.)

PROFESSIONAL PUBLICATIONS:

1. L.E. Dean, C.R. Johnson, H.J. Strasser, and P.S. Idell, "Electro-optical deep space surveillance: an update on Teal Amber I," Proc. SPIE **209**, Conference on Optical Signal Processing for C^3I, W.J. Micelli, ed.(1979).

2. S.R. Robinson and P.S. Idell, "A free-space propagation model for broadband optical fields," J. Opt. Soc. Am. **70**, 432-437 (1980).

3. P.S. Idell and J.W. Goodman, "Optimal imaging concentrators for partially coherent sources: absolute encircled energy criterion," J. Opt. Soc. Am. A **3**, 943-953 (1986).

4. P.S. Idell, "Optimal imaging concentrators for partially coherent sources: ratio of encircled energy criterion," J. Opt. Soc. Am. A **4**, 1911-1918 (1987).

5. P.S. Idell, J.R. Fienup, and R.S. Goodman, "Image synthesis from nonimaged laser-speckle patterns," Opt. Lett **12**, 858-860 (1987).

6. P.S. Idell and J.R. Fienup, "Imaging correlography with sparse collecting apertures," Proc. SPIE 828, Conference on Digital Image Recovery and Synthesis, P.S. Idell, ed., 140-148 (1987).

7. P.S. Idell (editor), "Digital Image Recovery and Synthesis," Proc. SPIE **828**, 195 pp. (1987).

8. J.R. Fienup and P.S. Idell, "Imaging correlography with sparse arrays of detectors," Opt. Engr. **27**, 778-784 (1988).

9. P.S. Idell, "Fundamental resolution limits for incoherently-averaged coherent images," Proc. SPIE **976**, Conference on Statistical Optics, M. Morris, ed., (1988).

10. D.G. Voelz, J.D. Gonglewski, and P.S. Idell, "Imaging correlography: experimental results and performance evaluation based on signal-to-noise ratio in the power spectrum estimate," Proc. SPIE **976**, Conference on Statistical Optics, M. Morris, ed., (1988).

11. P.S. Idell, J.D. Gonglewski, D.G. Voelz, and J. Knopp, "Image synthesis from nonimaged laser-speckle patterns: experimental verification," Opt. Lett. **14**, 154-156 (1989).

12. Y.Z. Hu, A. S. Marathay, and P. S. Idell, "Object reconstruction with intensity correlations," Proc. SPIE **1351**, Conference on Digital Image Synthesis and Inverse Optics, A.F. Gmitro, P.S. Idell, and I.J. LaHaie (editors), Paper 1351-59 (1990).

13. D.G. Voelz, J.D. Gonglewski, P.S. Idell, and D.C. Dayton, "Coherent image synthesis using a Shack-Hartmann wavefront sensor," Proc. SPIE **1351**, Conference on Digital Image Synthesis and Inverse Optics, A.F. Gmitro, P.S. Idell, and I.J. LaHaie (editors), Paper 1351-73 (1990).

14. P.S. Idell and J.D. Gonglewski, "Image synthesis from wave-front sensor measurements of a coherent diffraction field," Opt. Lett. **15**, 1309-1311 (1990).

15. A.F. Gmitro, P.S. Idell, and I.J. LaHaie (editors), "Digital Image Synthesis and Inverse Optics," Proc. SPIE **1351** (1990).

16. P. S. Idell, "Resolution limits for high-resolution imaging lidar," Proc. SPIE **1416**, R. J. Becherer, (editor), Paper 1416-35 (1991).

17. D. G. Voelz, P. S. Idell, K. Bush, and D. C. Dayton, "Illumination coherence effects in laser-speckle imaging," Proc. SPIE **1416**, R. J. Becherer, (editor), Paper 1416-36 (1991).

18. D.G. Voelz, J.D. Gonglewski, and P.S. Idell, "Imaging correlography: comparison of theoretical predictions with laboratory results," accepted for publication in Applied Optics.

19. P.S. Idell and A. Webster, "Fundamental resolution limits for photon noise-limited, coherent images," (accepted for publication in J. Opt. Soc. Am. A.).

CONFERENCE PAPERS:

1. P.S. Idell and J. W. Goodman, "Effects of coherence on optimal imaging concentrators," presented at the 1985 Annual Meeting of the Optical Society of America, Washington, DC, 14-18 October 1985.

2. P.S. Idell, "Optimal imaging concentrators based on the ratio of encircled energy criterion," presented at the 1986 Annual Meeting of the Optical Society of America, Seattle, WA, 20-24 October 1986.

3. 4. P.S. Idell and J.R. Fienup, "Imaging correlography: a new approach to active imaging," presented at the 12th DARPA Strategic Systems Symposium, Naval Postgraduate School, Monterey, CA, 28-30 October 1986 (classified proceedings available from the Riverside Research Institute, Arlington, VA).

4. P.S. Idell and J.R. Fienup, "Image synthesis from nonimaged laser speckle patterns: imaging correlography," presented at the 17th Winter Colloquium on Quantum Electronics, Snowbird, UT, 6-8 January 1988 (poster paper).

5. P.S. Idell and J.D. Gonglewski, D.G. Voelz, and J. Knopp, "Image synthesis from nonimaged laser speckle patterns: experimental verification," presented at the 1987 Annual Meeting of the Optical Society of America, Rochester, NY, 19-23 October 1987.

6. J.R. Fienup, R.S. Goodman, and P.S. Idell, "Incoherent image reconstruction from multiple laser speckle patterns," presented at the 1987 Annual Meeting of the Optical Society of America, Rochester, NY, 19-23 October 1987.

7. P.S. Idell and J.D. Gonglewski, and D.G. Voelz, "Image synthesis from nonimaged laser speckle patterns: experimental verification of imaging correlography," presented at the 13th DARPA Strategic Systems Symposium, Naval Postgraduate School, Monterey, CA, 20-23 October 1987 (classified proceedings available from the Riverside Research Institute, Arlington, VA).

8. P.S. Idell, "Active versus passive pupil plane imaging: a comparison of two approaches to intensity interferometry," presented at the 18th Winter Colloquium on Quantum Electronics, Snowbird, UT, 6-8 January 1988 (invited paper).

9. P.S. Idell, J.D. Gonglewski, D.G. Voelz, and B.M. Levine, "Experimental investigation of scintillation on images recovered from intensity interferometry data," presented at the 1988 Annual Meeting of the Optical Society of America, Santa Clara, CA, October 1988.

10. A.S. Marathay, Y.-Z. Hu, and P.S. Idell, "Image synthesis from third and fourth-order correlations of intensity," presented at the IEEE Conference on Multidimensional Signal Processing, Vail, CO, 28-30 June 1989.

11. P.S. Idell and J.D. Gonglewski, "Coherent image synthesis from wavefront-slope measurements of a nonimaged laser-speckle field," presented at the OSA Special Topics Conference on Signal Recovery and Synthesis, North Falmouth, Cape Cod, MA, 14-16 June 1989.

12: P.S. Idell, "Resolution limits for photocount noise-limited, coherent imaging systems," presented at the 1990 Annual Meeting of the Optical Society of America, Boston, MA, 5-9 November 1990 (Paper FZ7).

DISTRIBUTION LIST FOR ADVANCED RESEARCH PROJECT

TITLE: Space Policy for Laser Imaging of Foreign Satellites

AUTHOR(S): Paul S. Idell, Major, USAF

NWC #: ______ Office Use   **ARP #:** ______ Office Use

DISTRIBUTION:

I. INTERNAL

A. ARP RESERVE: ORIGINAL PLUS TWO PRINTED COPIES

COPY # ______
COPY # ______

B. LIBRARY DEPOSIT: Total 4

COPY # ______ MAIN LIBRARY
COPY # ______ WGD LIBRARY
COPY # ______ DTIC
COPY # ______ DTIC

C. FACULTY ADVISOR(S):

COPY #	ADVISOR	CODE
	Prof. S. Fought (NSDM Dept)	
	Col. Rocky Roland (OPS Dept.)	

D. OTHER:

COPY #	NAME	CODE

II. EXTERNAL ACTIVITIES/AGENCIES:

692-7011

COPY #	ACTIVITY	COMPLETE ADDRESS	ATTENTION
✓1.	JCS-J5	The Pentagon, Washington, DC 20318-5000	Col. Chadbourne
✓2	JCS-J36	" " " " " "	L/C R. Miller
✓3	OSD-ISP	" " " " " "	Ms. B. Masters
✓4	SAF/AQSD	" " " " " "	Maj. K. Loree
5	Hq AFSPACECOM/DOJ	STOP 7 Peterson AFB, CO 80914	L/C. J. Rabins
6	USSPACECOM/J35OT	Peterson AFB, CO 80914	Lt. J. Thilenius
✓7	PL/LI	Kirtland AFB, NM 87117-6008	Col. J. Otten
✓8	PL/LM	" " " " "	Dr. J. Fender
✓9	PL/LMI	" " " " "	L/C. D. Stone
✓10	PL/LTE	" " " " "	Maj. J. Anderson

COPY #	ACTIVITY	COMPLETE ADDRESS	ATTENTION
✓11	WL/MLPJ,	Wright-Patterson AFB, OH 45433	Dr. K. White
	~~MIT/Lincoln Laboratory, Group 52,~~	~~244 Wood Street, Lexington, MA 02173-9108~~	~~Dr. W.E. Keicher~~
✓12	NAVSPASUR,	Code 02, Dahlgren, VA 22448-5180	Dr. S.H. Knowles
✓13	U.S. Army SDC,	Code CSSD-SA-SC, Huntsville, AL 35807-3801	Jeff Randorf
✓14	Phillips Laboratory (OL-YY),	535 Lipoa Parkway, Suite 200 Kihei, HI 96753	Maj B. Smith
✓15	Phillips Laboratory (SXSM),	Kirtland AFB, NM 87117-6008	Maj. L. Johnson
✓16	Commanding Officer, Naval Research Laboratory,	Code 6550, 4555 Overlook Ave., SW., Washington, DC ~~[illegible]~~ 20375-5000	Dr. M. Pauli (Code 6550)
✓17	Phillips Laboratory (XPC),	Kirtland AFB, NM 87117-6008	L/C T. Dyble
18	1013 CCTS/DOS,	Peterson AFB, CO 80909	Capt. Lootens
✓19	Phillips Laboratory (LMI),	Kirtland AFB, NM 87117-6008	Dr. D. Voelz
✓20	SAF/SX,	the Pentagon, Room 4D939, Washington, DC 20330-1000	Col. T. Mervosh
21	AFSPACECOM/INY,	Peterson AFB, CO 80914	Mr. S. Pease

Attach additional sheets to add external activities or agencies requiring your project. Please note: If the project is classified, list the code or name of the person to receive this accountable document. Be sure the address is complete with zip code to insure safe and direct delivery. If help is needed to obtain the address, there is several books located in the secretaries office, please utilize these listings. If address is no good this could delay or even cause your project not to be sent to a requested agency.

TOTAL COPIES:

RESEARCH ASSOCIATE(S) FORWARDING ADDRESS:

ADVANCE RESEARCH PROJECT CERTIFICATION

PROJECT TITLE

SPACE POLICY FOR LASER IMAGING OF FOREIGN SPACECRAFT

STUDENT NAME(S)

PAUL S.IDELL
Major, USAF

I/we submit this paper to the Director of the Advanced Research Program in partial satisfaction of the requirements of the Center for Naval Warfare Studies.

Signature: Paul Idell
Signature: ______
Signature: ______
Signature: ______

Full Name of Faculty Advisor: Stephen O. Fought
Signature: ______
Academic/Staff Title: Dir, Defense Analysis Course NSDM

Per Naval War College Research Guide, I certify that this paper is substantively acceptable, and that this manuscript is free of typographical, spelling, and other grammatical errors and is ready for evaluation.

Date: 17 Mar 92

Advisor's Signature: ______

Enclosure (3)

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS
FOR OFFICIAL USE ONLY

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
DISTRIBUTION LIMITED TO U.S.
GOVERNMENT AGENCIES ONLY

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
ADVANCED RESEARCH PROGRAM
U.S. NAVAL WAR COLLEGE

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
U.S. NAVAL WAR COLLEGE
NETC NEWPORT, RI 02841-5010

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
Space Policy for Laser Illumination of Foreign Satellites

12. PERSONAL AUTHOR(S)
Idell, Paul Steven

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM ______ TO ______

14. DATE OF REPORT *(Year, Month, Day)*
1992, March, 13

15. PAGE COUNT
129

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Lasers Satellites Space Surveillance Imaging
Military Space Policy Space Warfare Adaptive Optics

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Current U.S. Department of Defense policy prohibits the laser illumination of any spacecraft without the explicit permission to do so from the satellite's owner. This policy places limitations on the ability to evaluate emerging laser imaging technologies for routine surveillance and imaging of foreign spacecraft. In order to identify satellite imaging regimes which will admit the application of ground-based laser imaging, a review of pertinent aspects of space law, U.S. policies, and current DOD procedures for controlling the emission of laser energy into space is conducted. Next, the laser illumination requirements for four proposed satellite imaging techniques are reviewed and their threat to spacecraft components is assessed. From this assessment, it is concluded that while these laser imaging techniques present an in-band damage threat to many earth-viewing optical sensors, they do not threaten the normal operation of other, non-optical satellites. Based on these results, modifications to the current

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
LCDR J.C. BENIGNO, USN, DEPUTY DIR., ARP

22b. TELEPHONE *(Include Area Code)*
401-841-3304/3259

22c. OFFICE SYMBOL
35A

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

☆U.S. Government Printing Office: 1985—639-012

0102-LF-014-6602

BLOCK 19 (cont.)

DOD laser illumination policy are drafted and evaluated, together with the current policy, on the basis of their ability to (1) protect U.S. space assets, (2) promote international cooperation in space, and (3) preserve U.S. freedom of action in space. It is concluded that cooperative, protective measures worked out between the satellite owner/operators and the laser operators to reduce the vulnerability of spaceborne optical sensors may be needed to allow routine operations of ground-based laser imaging systems against foreign satellites.