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Michael R. LaPointe and Steven R. Oleson
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

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LOW POWER GROUND-BASED LASER ILLUMINATION FOR ELECTRIC PROPULSION APPLICATIONS

Michael R. LaPointe and Steven R. Oleson
Sverdrup Technology, Inc.
LeRC Group, Brook Park, OH 44142

ABSTRACT

A preliminary evaluation of low power, ground-based laser powered electric propulsion systems is presented. A review of available and near-term laser, photovoltaic, and adaptive optic systems indicates that approximately 5-kW of ground-based laser power can be delivered at an equivalent 1-sun intensity to an orbit of approximately 2000 km. Laser illumination at the proper wavelength can double photovoltaic array conversion efficiencies compared to efficiencies obtained with solar illumination at the same intensity, allowing a reduction in array mass. The reduced array mass allows extra propellant to be carried with no penalty in total spacecraft mass. The extra propellant mass can extend the satellite life in orbit, allowing additional revenue to be generated. A trade study using realistic cost estimates and conservative ground station viewing capability was performed to estimate the number of communication satellites which must be illuminated to make a proliferated system of laser ground stations economically attractive. The required number of satellites is typically below that of proposed communication satellite constellations, indicating that low power ground-based laser beaming may be commercially viable. However, near-term advances in low specific mass solar arrays and high energy density batteries for LEO applications would render the ground-based laser system impracticable.

I_{sp}	specific impulse (s)
LACE	Low-Power Atmospheric Compensation Experiment
LEO	Low Earth Orbit
LLNL	Lawrence Livermore National Laboratory
M_0	total initial spacecraft mass (kg)
M_p	expended propellant mass (kg)
MIRACL	Mid-InfraRed Advanced Chemical Laser
MPD	magnetoplasmadynamic thruster
N_y	extended satellite life in orbit (y)
Nd:YAG	neodymium:yttrium aluminum garnet
P_L	laser power (W)
PIT	pulsed inductive thruster
PPT	pulsed plasma thruster
r_0	initial beam radius (m)
r_{spot}	final beam radius (m)
Si	silicon
SPT	stationary plasma thruster
SWAT	Short Wavelength Adaptive Techniques
Z	propagation distance (m)
α_m	molecular absorption coefficient (m^{-1})
α_a	aerosol absorption coefficient (m^{-1})
β_m	molecular scattering coefficient (m^{-1})
β_a	aerosol scattering coefficient (m^{-1})
γ	atmospheric attenuation coefficient (m^{-1})
ΔV	velocity change, delta-V (m/s)
λ	wavelength (m)
τ	atmospheric transmittance
1-sun	equivalent 1-sun intensity (1.38 kW/m ²)

NOMENCLATURE

ACE	Atmospheric Compensation Experiment
APSA	Advanced Photovoltaic Solar Array
AVLIS	Atomic Vapor Laser Isotope Separation
C_{gs}	cost of laser ground station (\$)
DF	deuterium fluoride
FEL	free electron laser
g	acceleration due to gravity (9.8 m/s ²)
GaAs	gallium arsenide
GEO	Geosynchronous Earth Orbit (3.6x10 ⁷ m)
HF	hydrogen fluoride
I	intensity (W/m ²)
I_0	initial beam intensity (W/m ²)

I. INTRODUCTION

Laser power beaming has been advocated for a variety of spacecraft power, propulsion, and communication applications.¹⁻⁵ Early research focused on the design of multimewatt space-based lasers, and the development of suitable high power conversion technologies.¹ Orbiting laser power stations were proposed as a method to deliver power to a multitude of reusable orbit transfer vehicles, whose reuse could amortize the expense of a space transportation infrastructure.⁵ High power laser systems were envisioned to occupy stationary lunar orbits, providing continuous

power for bases, rovers, and lunar mining operations,⁶ and were proposed as a method to deliver power from Mars orbit to a base on the Martian surface as part of an ambitious program of planetary exploration.⁷

Although attractive in terms of potential benefits, several hurdles must be overcome in the design, development, and operation of multimegawatt space-based laser stations. High power chemical lasers are well developed and routinely used for industrial and military applications,^{1,8} but the need to continually replenish the chemical reactants would significantly increase the operating cost of a laser station in orbit. Solar-pumped lasers, which use solar radiation to induce lasant population inversions, have been successfully demonstrated at sub-kW power levels.^{1,9} However, a tremendous amount of work remains before these concepts can provide the high power, closed-cycle, autonomous operation required for the multimegawatt mission applications proposed above. Nuclear-pumped lasers, which utilize fission fragments to excite a lasant gas in a reactor core, have also been developed and tested at low power levels.^{1,10} However, continual postponements in the development and deployment of space nuclear power systems make it unlikely that a space-based nuclear-pumped laser will be available in the near future. Free electron lasers, in which coherent radiation is extracted from the periodic oscillations of high energy electron beams,¹¹ can generate high power levels but require significant development before they can provide reliable, long-term operation in the remote space environment.

Many of the issues associated with using space-based lasers are removed by keeping the laser stations on the ground, where operating power is readily available and the lasers are accessible for maintenance and upgrade. Enthusiasm for ground-based power beaming was initially tempered by the difficulties associated with propagating high power laser beams through the atmosphere. Atmospheric turbulence and temperature fluctuations change the atmospheric index of refraction along the beam propagation path,¹² producing distortions which can spread the beam and dramatically alter the intensity profile at the receiver. In the absence of atmospheric distortion, the beam will spread as it propagates due to diffraction at the beam source such that:

$$r_{\text{spot}} = \frac{0.61 Z \lambda}{r_0} \quad (\text{m}) \quad (1)$$

where r_0 is the initial beam radius, r_{spot} is the beam

radius after propagating a distance Z , and λ is the laser wavelength. The final beam or spot radius in Equation 1 corresponds to the first zero in the diffraction pattern at the receiver, which contains 84% of the initial beam energy. For a laser wavelength of 1.06 μm and an initial beam radius of 0.5 m, the spot radius at a distance of 500 km is approximately 0.65 m due to diffraction, which corresponds to a beam expansion half-angle (r_{spot}/Z) of approximately 1.3 μrad . In the absence of atmospheric effects, larger initial beam radii or smaller laser wavelengths could be used to further reduce the beam radius at the receiver.

The effect of atmospheric turbulence on beam propagation is a function of the atmospheric coherence distance,¹³ which is a measure of the lateral distance over which atmospheric fluctuations do not significantly effect beam propagation. The atmospheric coherence distance depends upon the path length, the beam propagation angle, and the refractive index structure "constant", a complex and decidedly non-constant variable which approximates the strength of the atmospheric turbulence. For wavelengths of interest to laser power beaming, the coherence distance is on the order of 0.1 m,¹⁴ which roughly corresponds to the maximum initial beam diameter that can be propagated through the atmosphere without serious degradation. For initial beam diameters smaller than the atmospheric coherence length, the final spot size is governed primarily by diffraction. For larger initial beam diameters, the final spot size is governed primarily by atmospheric turbulence. An initial beam diameter larger than the atmospheric coherence distance will not decrease the beam expansion caused by atmospheric turbulence. Instead, the beam will spread as if the effective initial beam diameter were equal to the atmospheric coherence distance.

The final spot radius of a beam propagating through the atmosphere is given by the addition of the beam expansion due to diffraction and the beam expansion due to atmospheric turbulence. For the parameters used in the above example, an initial beam radius equal to half the atmospheric coherence distance yields a spot radius of approximately 6.4 m, corresponding to an expansion half-angle of about 13 μrad due solely to atmospheric turbulence. The final spot radius for the example is then given by:

$$r_{\text{spot}} = (0.61)(5 \times 10^5 \text{ m})(1.06 \times 10^{-6} \text{ m})(0.5 \text{ m}) + (5 \times 10^5 \text{ m})(1.3 \times 10^{-5} \text{ rad}) \approx 7 \text{ m} \quad (2)$$

which is significantly larger than the 0.65 m spot

radius calculated for diffraction effects alone. A larger initial beam radius would reduce the diffractive component of beam spreading, but it would not alter the significantly larger beam expansion caused by atmospheric turbulence. The larger receiver area required to collect the expanded beam after it traverses the atmosphere increases the mass of the spacecraft, and mitigates the potential advantages of laser power beaming.

In addition, wavefront phase changes imparted by atmospheric fluctuations can produce localized regions of high beam intensity at the receiver, often of sufficient magnitude to damage or degrade receiver performance. Other concerns associated with high power beam propagation include thermal blooming,¹⁵ in which a fraction of the transmitted laser energy is absorbed by the atmosphere along the propagation path. The atmosphere becomes slightly heated, changing the refractive index and creating a negative lens along the beam path length. The beam spreads radially due to the negative atmospheric lensing, and may be further distorted by the asymmetric heat flow associated with atmospheric winds or by the laser beam slewing through the atmosphere. Without a suitable technique to compensate for these atmospheric aberrations, ground-based laser power beaming is not a particularly attractive option compared to conventional methods of spacecraft power and propulsion. Fortunately, methods to correct such atmospheric distortions exist in the form of adaptive optics.

Although still developmental, adaptive optics have been successfully used to correct the atmospheric distortion of astronomical objects and to beam laser energy through the atmosphere.¹⁶ Adaptive optic systems for astronomical applications typically consist of a telescope receiver, a wavefront sensor, an active or deformable mirror, and a control system to convert the output from the wavefront sensor into signals which control the deformable mirror (Figure 1). Light from a target star is collected by the telescope, and reflected from a fast steering tilt mirror to a deformable mirror. A portion of the light is sent from the deformable mirror to an imaging camera, and the remainder is sent to a wavefront sensor which measures the atmospherically induced phase perturbations across the telescope aperture. Because the star is an effective point source, the incoming light ought to be a plane wave. The phase perturbations measured by the wavefront sensor correspond to variations from the expected plane wave distribution. The phase perturbation measurements are converted into electri-

cal signals and used to drive the deformable mirror, which compensates for the phase distortions and flattens the incoming wave. With the use of adaptive optics, the image resolution can be nearly diffraction-limited. In addition to natural stars, laser guide stars have been used to provide point-like sources for adaptive optics when natural stars are too weak or too far from the desired point of observation. Techniques using Rayleigh backscatter¹⁷ and laser illumination of the Earth's sodium layer¹⁸ have provided effective synthetic beacons for the adaptive optics correction of astronomical objects.

Similar adaptive optic techniques may be used to propagate laser beams through the atmosphere. A natural star or synthetic beacon is used to provide a reference signal for the wavefront sensor. The wavefront sensor controls an active mirror, which deforms to fit the phase profile of the incoming distorted wavefront. The laser beam to be propagated through the atmosphere is reflected from the deformed mirror, which imparts a phase distortion to the outgoing wavefront that is the approximate conjugate of the phase distortions accumulated by the reference signal on its downward path through the atmosphere. As the predistorted outgoing wavefront propagates back along the same (or nearly the same) path through the atmosphere, the phase distortions are reversed, and a nearly diffraction-limited planar wavefront emerges from the atmosphere. For moving targets, the reference signal must be placed ahead of the target so that the reference signal and return beam propagate along approximately the same path through the atmosphere. For satellites in non-geosynchronous orbit, this requires the use of beacon lasers or retroreflectors placed on extended booms in the direction of motion (Figure 2), or synthetic Rayleigh or sodium layer beacons created at the correct point-ahead distance in the atmosphere so that the return laser beam intercepts the main satellite body (Figure 3).

The ability of adaptive optics to compensate for atmospherically induced laser beam aberrations has been demonstrated in a number of successful ground-to-space beam propagation experiments, performed over the past decade by the Massachusetts Institute of Technology Lincoln Laboratories under the aegis of the Department of Defense.¹⁹ Part of the Atmospheric Compensation Experiment (ACE) test series used a retroreflector carried aboard the space shuttle Discovery and a ground-based, 60-cm diameter deformable mirror to perform preliminary adaptive optic compensation experiments. An uncorrected laser beam was used to illuminate the retroreflector,

and the reflected signal was successfully corrected by the ACE adaptive optics. The experiment demonstrated atmospheric compensation of a dynamic target, but did not actually compensate an outgoing laser beam. A series of subsequent ACE tests were performed with sounding rockets, launched to altitudes of approximately 600 km.¹⁹ Each rocket carried a retroreflector to provide a synthetic beacon for the adaptive optics, and a linear array of detectors to measure beam compensation. The retroreflectors were illuminated with laser light at 488 nm, providing a synthetic beacon for the wavefront sensor. The wavefront information was used to control a deformable mirror, and a second laser at 514 nm was reflected from this mirror and detected by the passing rocket. The detector arrays recorded a dramatic increase in beam irradiance when the outgoing laser beam was compensated for atmospheric aberrations by the adaptive optics, and the tests were the first to successfully demonstrate the atmospheric compensation of a laser beam propagated from the ground-to-space.

Other programs at the MIT Lincoln Laboratory included the Short-Wavelength Adaptive Techniques (SWAT) test series,²⁰ which used atmospheric Rayleigh backscatter to create a synthetic beacon for compensated astronomical observations. Subsequent SWAT tests demonstrated retroreflector and synthetic beacon compensation techniques for power beaming to a satellite in LEO. In February 1990, the Low-Power Atmospheric Compensation Experiment (LACE) research satellite was placed into a 547 km, 43° inclination circular orbit. A corner cube array, located on an extendable boom and illuminated with an uncompensated ground-based laser, was used to provide a return signal for sensing the atmospheric distortion. The reflected signal was used by the ground-based adaptive optics to correct a second outgoing laser beam. This corrected beam was detected by an array of silicon photodetectors distributed in a 2-dimensional pattern on the satellite body. Real-time detector array data were used to evaluate the effectiveness of the compensation, and to drive a pointing loop which kept the outgoing beam centered on the array. The duration of an overhead pass, from a sighting elevation of 45° ascending to 45° descending, was 120 to 150 s, corresponding to a laser slew rate of approximately 10 mrad/s. The experiments, performed over a 15 month period, demonstrated the ability of the adaptive optics to compensate a ground-based laser beam for low earth orbit satellite applications. As part of the SWAT program, a synthetic beacon created in the atmosphere with Rayleigh backscatter was successfully used for LACE satellite

compensation experiments, providing the first demonstration of the synthetic beacon technique for compensated ground-to-satellite beam propagation.²⁰ The LACE satellite was decommissioned in February, 1993.

With a viable method to propagate ground-based laser energy through the atmosphere, high power lasers have again been advocated for space power and propulsion applications. Potential missions include the illumination of geosynchronous satellite solar arrays during eclipse periods,²¹ the illumination of thermal or electric propulsion orbital transfer vehicles,^{22,23} and the illumination from Earth of a lunar base during the 14-day lunar night.²⁴ Each of these applications require sustained laser powers of several hundred kilowatts to tens of megawatts, and as noted above the necessary laser systems are still being developed.

This paper presents a first order consideration of potential mission opportunities which can take advantage of adaptive optics acting in concert with available laser and power conversion systems. The following section presents an overview of available and near-term technologies for laser beam formation, propagation, conversion, and utilization for spacecraft propulsion. Section III outlines potential applications, including a look at low laser power ground-based beaming for commercial satellite constellations. The paper concludes with a brief summary of results, and suggestions for further research.

II. TECHNOLOGY REVIEW

The general requirements for ground-based laser power beaming include the ability to transmit the laser energy through the atmosphere without significant losses, the efficient conversion of the laser power to electrical power via photovoltaic conversion or the absorption of the laser power for thermal propulsion, and at least a competitive ability to perform a given mission. The following sections present an overview of atmospheric propagation issues, commercial and near-term laser and photovoltaic array technologies, and candidate electric propulsion systems which might be used for low power mission applications.

Atmospheric Propagation Issues.

In addition to the diffractive beam spreading discussed above, both linear and nonlinear atmospheric effects hamper the efficient propagation of laser energy from ground to space. Some linear effects,

such as atmospheric turbulence and fluctuations in the atmospheric refractive index, can be corrected using adaptive optics. Other linear effects, such as beam scattering and absorption by molecules and aerosols, or beam attenuation due to inclement weather, remove directed energy from the beam and cannot be corrected using adaptive optics. Nonlinear effects, such as thermal blooming and air breakdown, require laser beam intensities on the order of 10^6 - 10^8 W/cm². Such laser intensities are not expected to occur for the low power cw lasers considered in this study, and can be avoided in pulsed laser systems by keeping the pulsed beam intensities below these approximate thresholds.

Beam scattering and absorption by molecules and aerosols present the most serious challenge to beam propagation through the atmosphere. The atmospheric transmittance (τ) is defined as:²⁵

$$\tau = \frac{I(Z)}{I_0} = \exp\left[-\int_0^Z \gamma dz\right] \quad (3)$$

where $I(z)$ is the beam intensity after propagating a distance z through the atmosphere, I_0 is the initial beam intensity, and γ is the atmospheric attenuation coefficient, given by:

$$\gamma = \alpha_m + \alpha_a + \beta_m + \beta_a \quad (\text{m}^{-1}) \quad (4)$$

where α_m is the molecular absorption coefficient, α_a is the aerosol absorption coefficient, β_m is the molecular scattering coefficient (due to Rayleigh scattering), and β_a is the aerosol scattering coefficient (due to Mie scattering). Molecular absorption is highly dependent upon wavelength, and its proper evaluation requires a detailed knowledge of the spectroscopic parameters of thousands of absorption lines in the atmosphere. Molecular scattering is in general only important for ultraviolet radiation. Aerosol scattering is generally more important than aerosol absorption. Aerosol attenuation is a slowly varying function of wavelength, and is generally less important at longer wavelengths. Figure 4 shows a low resolution plot of atmospheric transmittance versus wavelength from 0-15 microns. Numerous atmospheric absorption lines exist which are not shown on the low resolution plot,²⁵ and atmospheric transmission models are continually being upgraded to better resolve the effects of narrow band absorption on atmospheric laser beam propagation.

Candidate Laser Systems.

A variety of lasers have been developed and tested under laboratory conditions, but only a few commer-

cial laser types exist which are of interest for power beaming applications. The following brief descriptions are compiled from the *1986 Laser Guidebook*,²⁶ the *1990 Lasers and Optronics Buyer's Guide*,²⁷ and the *1993 Laser Focus World Buyer's Guide*,²⁸ with additional information provided by the cited references. The descriptions are not intended to provide a comprehensive tutorial on all possible laser systems of interest, but rather serve to illustrate the general nature of commercially available lasers which might be considered for near-term power beaming applications.

Dye lasers use a fluorescent organic dye in a liquid solvent as the lasing medium. Intense illumination by a separate source (flashlamp, ion laser, copper vapor or Nd:YAG laser) excites the dye molecules to produce a population inversion. The dye then undergoes stimulated emission to produce a laser beam. Dye lasers are tunable from roughly 300 nm to 1000 nm, depending upon the dye. Depending upon the pump source, average or cw powers can vary from several tens of watts for commercial units to kilowatt-class special order lasers. Beam diameters may range from slightly less than 1 mm up to 20 mm, with beam divergence angles of 0.3 mrad to 6 mrad. Laser dye solutions have limited lifetimes ranging from several hours to several months, and flashlamp lifetimes are limited from 10^4 - 10^6 shots before replacement is required. The laser systems are not particularly robust, and rough handling could damage the liquid flow system and misalign the optics. Laser dyes and solvents can be toxic, and most are flammable both in liquid and vapor form. Typical costs for the higher power commercial dye lasers range from \$50,000 to \$100,000.

Noble gas *ion lasers* use argon, krypton, or a combination of the two gases. A high current discharge is used to ionize the gas and induce the required population inversions. The lasers operate in continuous-wave mode, but may be modelocked for pulsed operation. Multiline argon-ion laser output powers may reach several tens of watts, with single-line operation at lower power levels. The less efficient krypton-ion lasers can produce up to a few watts of multiline power. Argon-ion lasers emit at several wavelengths from 351-528 nm, with main emission lines at 488 nm and 514.5 nm. Krypton-ion lasers emit several lines between 350-800 nm, with a main line at 647.1 nm. The lasers are long-lived, with lifetimes exceeding several thousands of hours. Beam diameters range from 0.6 mm to 2 mm, with

divergence angles between 0.4 to 1.5 mrad. Although efficiency is not a primary concern for ground-based lasers, ion lasers achieve overall efficiencies significantly below 0.01% for multiline operation, and less for single line operation. Dye lasers, by contrast, may achieve up to a 25% conversion of the pump light into laser light. A typical cost for an argon-ion laser capable of providing several watts of power is on the order of \$50,000.

Neodymium lasers constitute a class of semiconductor lasers in which neodymium is used as a dopant in various host materials. The most common neodymium laser is the Nd:YAG, in which a synthetic crystal of yttrium aluminum garnet (YAG) serves as a host for the neodymium impurity. Alternative host materials include yttrium lithium fluoride and yttrium aluminate, although neither enjoys the wide commercial acceptance of Nd:YAG. The lasers are generally pumped by flashlamps to produce the required population inversions, although diode pumped Nd:YAG lasers have been operated at sub-Watt power levels. Continuous or pulsed powers of several hundred watts are available in commercial Nd:YAG lasers at a wavelength of 1.06 microns. Multiple-rod cavity designs and laser coupling techniques have been used to achieve Nd:YAG cw-power levels up to a few kW.²⁹ Lifetimes are generally limited by the pump flashlamps to around 10⁶ shots. Beam diameters range from roughly 1 mm to 10 mm, with beam divergence angles of a few mrad to tens of mrad. Such large divergence angles may present focusing and collimation problems in beamed power applications. Neodymium lasers have been used for a variety of applications ranging from military targeting to industrial welding, and have proven to be quite robust under most operating conditions. The cost of commercially available high power Nd:YAG laser systems is on the order of \$100,000 - \$200,000.

Chemical lasers, such as the hydrogen fluoride and deuterium fluoride lasers, use chemical reactions to excite a light-emitting species. Hydrogen fluoride (HF) emits at 2.6 to 3.3 microns, a region where atmospheric absorption is strong. Deuterium fluoride (DF) lasers operate in the wavelength range of 3.5 to 4.2 microns, where atmospheric transmission is good but the efficiency is lower and costs are higher due to the use of deuterium. Large chemical laser facilities have been built for military weapons research. The Mid-InfraRed Advanced Chemical Laser (MIRACL) laser is a DF laser which reportedly can produce up to 2 MW of continuous power, and a large HF laser

known as Alpha has been designed to produce 5 MW of cw power. Lower power Hf and DF lasers are commercially available, with multiline continuous power levels up to 150 W. Pulsed laser systems are also available with energies ranging from 2-600 mJ with pulse repetition frequencies of 0.5-20 Hz. Typical beam diameters are 2-40 mm, and beam divergence angles range from 1-15 mrad. The lasers require maintenance every 50-100 hours, primarily to change vacuum pump oil and clean the H₂ or D₂ injectors. A typical cost for a 150-W commercial DF laser is on the order of \$90,000.

Carbon dioxide lasers can produce continuous power levels from milliwatts to several kilowatts at wavelengths between 9 and 11 microns, with single line operation at 10.6 μ m commonly available. The lasers are robust, with lifetimes of several thousands of hours. Beam diameters range up to several mm, with typical beam divergence angles of a few mrad. Power conversion efficiencies range from 5-15%, and costs for the higher power 5-15 kW CO₂ lasers may run to several hundred thousand dollars. Photovoltaic cells do not respond to radiation at 10.6 microns, however, and the CO₂ laser is thus not suited for power beaming to an electric thruster. However, the CO₂ laser may be useful for concepts which directly absorb the laser energy to heat a propellant.

Copper vapor lasers are inherently pulsed lasers which operate at repetition rates of several kilohertz. The copper is heated and mixed with neon, producing a vapor which acts as the active laser medium. A fast electrical discharge is used to directly excite the vaporized copper atoms, producing a population inversion and subsequent laser emission. Copper vapor lasers emit two lines simultaneously, at 510.6 nm and 578.2 nm, which can be separated in the output beam. Average power levels in commercial units range from a few watts to tens of watts, with overall efficiencies slightly below 1%. Beam diameters range from 20 to 80 mm, with divergence angles of 3-5 mrad. Smaller divergence angles of 0.3-0.5 mrad may be obtained with unstable resonators at the cost of reduced laser power levels. Due to the migration of copper from the discharge region, new metal must be loaded into the discharge tube after a few hundred hours of operation. With copper replenishment, commercial units have expected lifetimes of a few thousand hours. Depending upon the power level, commercial copper vapor lasers cost from \$30,000 to \$100,000 per unit, with the cost of replacement tubes ranging from \$600 to \$10,000.

High power copper vapor lasers have been used for a number of years at the Lawrence Livermore National Laboratory (LLNL) as part of the uranium isotope separation facility.³⁰ The Atomic Vapor Laser Isotope Separation (AVLIS) facility uses a chain of twelve copper vapor lasers to pump dye lasers, which in turn are used in the isotope separation process. The copper vapor lasers produce roughly 10 kW of pulsed power with a beam quality roughly 15 times the diffraction limit, with a planned upgrade to 15 kW average power and a beam quality roughly five times the diffraction limit. LLNL has recently used a copper vapor laser to pump a dye laser to produce a synthetic guide star in the atmospheric sodium layer.³¹ The pulsed output of the dye laser, tuned to 589 nm, was directed through a 1 meter telescope to produce a fluorescence beacon in the sodium layer. The pulsed laser combination produced an incident power of 1 kW, roughly four times the power required to saturate the sodium layer atoms. LLNL is currently investigating pulse-stretching techniques to increase the return signal intensity.

Semiconductor diode lasers have recently been manufactured which can produce up to 1 Watt of continuous power at wavelengths from 770 nm to 840 nm. The lasers are made by metal-organic-chemical vapor deposition, with a typical emission region of only $160 \mu\text{m} \times 1 \mu\text{m}$. Advances in fabrication technology make possible the construction of several thousand emitting regions packed in closely spaced arrays, allowing potentially high power laser operation. To provide a useful kW-class beam at the receiver, several thousand diode lasers would have to be coherently combined and controlled, which is beyond the present capability of current phase locking technology. Other issues include the integration of electrical current controls for each of the laser diodes, and sufficient heat removal from packed, heat-sensitive diode arrays. Although a suitable kW-class diode array is not presently available, continued advancements in semiconductor laser diode arrays may make this a promising near-term technology for ground-to-space power beaming applications.

Kilowatt-class *free electron lasers* (FELs) are being developed for commercial application, but to date are expensive, complex, and not generally available. High power near-infrared FELs can be designed and manufactured to suit individual user needs, but at tremendous cost. The component technologies typically require large operating areas, and the devices are not particularly robust. Trends for commercial

development are geared more toward FEL user facilities, where researchers may sign up for time on the laser.³² A compact FEL is being developed for commercial use at wavelengths from 30-1000 μm ,³² which unfortunately are not suitable for photovoltaic conversion applications. There is no particular commercial driver for lower power FEL lasers at wavelengths of interest for ground-to-space power beaming, and it is not likely that FEL technology will be available for near-term mission applications. The potential military and commercial uses for multimewatt free electron lasers provide sufficient impetus for the continued development of FELs, which may eventually find additional applications in the high power ground-to-space laser beaming applications discussed above.

Based on the brief reviews presented above, Nd:YAG or copper vapor laser pumped dye lasers may offer the best available technologies for ground-based power beaming to photovoltaic receivers. High laser powers can be achieved by coherently combining the output of several individual lasers, and total power levels of a few kW are probably realistic. The better beam quality of copper vapor laser pumped dye lasers may give them an advantage over neodymium-based lasers in terms of collimation and focusing, but the shorter discharge tube lifetimes will require more frequent maintenance and replacement. Coherent semiconductor diode laser arrays are a promising near-term technology for achieving kilowatt power levels at wavelengths of interest for photovoltaic conversion, provided issues of phase locking and heat removal can be adequately addressed.

Photovoltaic Receivers.

Photovoltaic cells illuminated by solar radiation have been extensively used to provide electrical power for a variety of spacecraft applications. Several photovoltaic materials have been developed to convert solar illumination to electrical power, as illustrated in Figure 5. The most mature cell technologies, silicon and gallium arsenide, have solar conversion efficiencies of approximately 18-20% and 23-24%, respectively, measured in vacuum (air-mass zero) at a solar intensity of 1 sun (1.38 kW/m^2). The photovoltaic conversion efficiency can be considerably higher under monochromatic illumination, as illustrated in Figure 6. Between 800-1000 nm, the photovoltaic conversion efficiency of silicon cells increases to approximately 40%, double the conversion efficiency under solar illumination at comparable intensities. The conversion efficiency of gallium arsenide cells

increases to over 50% at wavelengths between 800-860 nm, again doubling the conversion efficiency achieved with comparable intensities of solar illumination.

The cell efficiencies displayed in Figure 6 drop off fairly linearly at wavelengths below optimum, and fall rapidly to zero for wavelengths larger than the optimum wavelengths. The necessity to operate at or near the optimum wavelengths for efficient power conversion places additional constraints on the laser systems which may be used for power beaming. The copper vapor laser, which operates at wavelengths of 510.6 and 578.2 nm, does not provide significantly improved performance for silicon arrays compared to the achievable conversion efficiency under solar illumination. Somewhat better performance is achieved by gallium arsenide arrays, with an increase in conversion efficiency from approximately 25% under solar illumination to roughly 35-40% under copper vapor laser illumination at the same intensity. Using the copper vapor laser to pump a dye laser may provide better efficiencies, as the dye laser can be tuned to coincide with the optimum wavelengths for efficient conversion. Copper vapor lasers are inherently pulsed systems, however, and issues with efficient cell conversion under pulsed laser illumination must be addressed. If the pulse repetition period is shorter than the minority carrier lifetime of the photovoltaic cell, the cell responds to the laser illumination as if it were essentially a cw laser operating at the average laser power. If the pulse repetition period is longer than the minority carrier lifetime of the cell, the cell responds to each individual pulse at the peak laser power. The power lost to series resistance in the cell increases linearly with peak incident power, and the cells must be designed to minimize series resistance losses under pulsed illumination.^{33,34}

Neodymium lasers operate at 1.06 μm , slightly beyond the optimum wavelength range for silicon cells and considerably beyond the wavelength range suitable for gallium arsenide cells. At 1.06 μm , the silicon cell efficiency is approximately 15%, slightly less than the conversion efficiency achieved with solar illumination. There is evidence that operating the silicon cells at high temperatures improves the efficiency at longer wavelengths,³⁵ and peak cell responses have been shifted to wavelengths as long as 1.03 μm . Additional techniques such as light trapping³⁶ might be used to further improve silicon cell conversion efficiencies under Nd:YAG illumination. As noted in Figure 6, CuInSe_2 cells have a peak response of about 28% at 1.06 μm , compared to a cell

response of 12-18% under solar illumination. Although capable of providing better conversion efficiencies than standard silicon cells under Nd:YAG illumination, CuInSe_2 cells are still developmental.

With wavelengths between 770-840 nm, semiconductor diode lasers are nearly optimum for illuminating both silicon and gallium arsenide arrays. Unfortunately, the technology necessary to produce kilowatts of power from a coherent array of several thousand semiconductor diode lasers must still be developed. Deuterium fluoride laser wavelengths, ranging from 3.5-4.2 μm , are too long to be efficiently converted with photovoltaic arrays, even with frequency doubling. Successive doubling could move the operating wavelengths to the correct region for conversion, but at the cost of significantly reduced laser powers and added system complexity.

Current solar array designs consist of planar rigid panel arrays, flexible fold-out planar arrays, and concentrator arrays. Rigid panel silicon arrays³⁷ are the most commonly used to date, with panel specific masses of around 23 kg/kW. Total array specific masses, including the panel, hinges, booms, harnesses, support structures, power transfer, and launch retention mountings, are on the order of 35 kg/kW. Gallium arsenide rigid panel arrays³⁷ have a panel specific mass of about 19 kg/kW, and a total array specific mass of around 30 kg/kW. The most advanced fold-out array currently being developed is the Advanced Photovoltaic Solar Array (APSA),^{37,38} which consists of silicon cells on a kapton blanket. The specific mass of the APSA array panel is 7.2 kg/kW. Using thin film CuInSe_2 cells, the projected specific mass is lowered to around 5 kg/kW. Concentrator arrays, which focus incident light onto a small area of photovoltaic cells, are designed to increase the intensity and power output over that achievable under 1-sun illumination. Estimated specific masses for conceptual fresnel lens concentrator panels³⁷ are on the order of 15 kg/kW.

The improved efficiency of photovoltaic arrays under laser illumination allows the array mass at a given power level to be reduced. For example, a rigid planar silicon array has an efficiency of around 18% under solar illumination and a specific power of 35 kg/kW. To produce 1 kW of power under solar illumination, the total array mass would be on the order of 35 kg. Because the efficiency of this same array is nearly doubled under laser illumination of the proper frequency at the same intensity, an array mass of only 17.5 kg would be required to produce the

same 1 kW of power. The mass savings could result in lower launch costs, or additional propellant could be carried along to increase the operational life of the satellite.

Low Power Electric Propulsion.

Significant propellant mass reductions or extended spacecraft orbital lifetimes can be achieved using electric propulsion, which provides higher specific impulse (I_{sp}) than chemical auxiliary propulsion systems. For a given I_{sp} , the propellant mass (M_p) required to produce a velocity change ΔV for a spacecraft with initial mass M_0 is given by:

$$M_p = M_0 \{1 - \exp[-\Delta V/(g \cdot I_{sp})]\} \quad (\text{kg}) \quad (5)$$

where g is the acceleration due to gravity (9.8 m/s^2). Engines which provide higher I_{sp} values require less propellant for a given ΔV , conserving the propellant carried into orbit or reducing the launch mass and cost.

Auxiliary chemical propulsion systems for long-term satellite stationkeeping applications use monopropellant hydrazine thrusters, with a specific impulse of around 220 s, or nitrogen tetroxide/monomethyl hydrazine (NTO/MMH) bipropellant thrusters, with a specific impulse value of approximately 310 s. Iridium-coated rhenium rockets capable of operating at high chamber temperatures are being developed,³⁹ which may provide an increase of tens of seconds in I_{sp} over current chemical auxiliary propulsion systems. Monopropellant hydrazine and NTO/MMH have been used for satellite maneuvering and stationkeeping applications. Due to the reduced system complexity, monopropellant hydrazine thrusters have been preferred for small satellite propulsion applications.

The performance of monopropellant hydrazine thrusters, in which the liquid hydrazine propellant is decomposed to constituent gases before expansion through a nozzle, can be augmented by passing the decomposed propellant through a heat exchanger resistively heated by an electric current. Resistively heated thrusters (*resistojets*) have been operated with a variety of propellants.⁴⁰ The most prevalent resistojet systems use hydrazine propellant, with propellant storage and feed systems nearly identical to conventional hydrazine thrusters. The augmented catalytic thruster (ACT)⁴¹ has demonstrated long life performance with I_{sp} values approaching 305 s (Figure 7a) with thrust levels of 0.18-0.34 N (Figure 7b) for

heater powers approaching 500 W.

Kilowatt-class hydrazine *arcjets* have been developed for stationkeeping applications.⁴² Arcjets heat a propellant via an electrical arc struck between a cathode and concentric anode, with the anode serving as a nozzle for propellant expansion. The propellant temperature significantly exceeds the temperature achievable with chemical rockets or resistojets, providing substantially higher values of specific impulse. Figure 8 displays specific impulse versus power for various hydrazine decomposition product mass flow rates, for power levels from 0.3-1.1 kW. I_{sp} and thrust values of approximately 450 s and 0.16 N, respectively, were achieved for mass flow rates of $3.73 \times 10^{-5} \text{ kg/s}$ at input power levels approaching 1 kW.

A flight qualified 1.8-kW hydrazine arcjet has been developed for north/south stationkeeping duties on the Martin Marietta Series 7000 geosynchronous communication satellites.⁴³ The arcjet produces a mission average specific impulse of 520 s, and has demonstrated an equivalent mission lifetime in excess of 12 years. Measured thrust was between 0.15-0.3 N, depending upon the propellant mass flow rate. The 1.8 kW arcjet has been baselined for use on the AT&T Telstar 4 satellite, scheduled for impending launch. Developmental work continues on low power hydrogen arcjets, which can attain specific impulse values of 650-1200 s at power levels of 1-4 kW.⁴³

Solid propellant *pulsed plasma thrusters* (PPTs) have been used on a variety of spacecraft for drag makeup and stationkeeping.⁴⁴ A solid fluorinated polymer bar is inserted between two planar electrodes, and an arc is struck across the face of the bar, ablating material. The material is accelerated via Lorentz forces arising from the interaction of the discharge current and an induced perpendicular magnetic field, with gas-dynamic forces accelerating the remaining ablated neutral propellant mass. Specific impulse values vary from 300-1500 s. Average powers are on the order of tens of watts, with peak powers during discharge approaching a few megawatts. A pair of PPTs are currently in use on each of the U.S. Navy TIP/NOVA navigation satellites, providing approximately 0.4 mN-s impulse bits per thruster. On the average, each pair of thrusters fire slightly more than once per minute to keep the satellites in a precisely defined orbit.⁴⁵ With a calculated lifetime of 65 million firings per thruster, the initial fuel mass of 1 lb (0.453 kg) per thruster will last approximately 22

years.

Stationary plasma thrusters (SPTs) have been developed and flown on several Soviet spacecraft.⁴⁴ The SPT sustains an electric discharge between an external cathode and an anode channel, which ionizes a propellant gas. Ions are accelerated by the channel electric field, and the plasma is volume neutralized by cathode electrons. SPT's have been operated with xenon propellants at powers up to 700 W, providing I_{sp} values from 1000-2000 s at thrust levels of around 0.03 N. The SPT's have successfully operated for several hundred hours in orbit, and for several thousand hours of ground testing.⁴⁶

Ion thrusters have been investigated for auxiliary and primary propulsion for several years.⁴⁷ Ions are formed in a discharge chamber through collisions with electrons emitted from a hollow cathode. The ions are electrostatically accelerated through a set of charged, perforated ion optics, and the beam is volume neutralized by electrons emitted from a second hollow cathode placed outside the discharge chamber. High power mercury ion thrusters operated at power levels of 20-200 kW achieved specific impulse values of several thousand seconds. Current research efforts are focused on the development of inert gas ion thrusters operated at 0.5-5.0 kW, which take advantage of the modest power levels currently available for spacecraft applications.

NASA has taken a low-risk approach to facilitate implementation of low power ion thruster technology for auxiliary propulsion.⁴⁸ In this approach, a 30-cm xenon ion thruster, originally developed for higher power primary propulsion, is instead operated at a fraction of its design power level. Figures 9a and 9b show measured specific impulse and thrust values for a derated 30-cm ion thruster operated with xenon propellant at power levels between 0.25-2.0 kW.⁴⁸ The specific impulse varies from a low of 1000 s at 250 W to approximately 2500 s at 2 kW, with a peak thrust-to-power ratio of 57 mN/kW. Advantages to using a derated thruster for auxiliary propulsion include the elimination of known life limiting issues, increased thrust-to-power ratios, and reduced flight qualification times.⁴⁸

Magnetoplasmadynamic (MPD) thrusters use electromagnetic acceleration to achieve high specific impulse. An arc struck between two concentric electrodes ionizes a neutral propellant gas, which is then accelerated by the Lorentz force arising from the

interaction of the discharge current with self-induced and/or applied magnetic fields.⁴⁹ Additional acceleration is provided in applied-field devices by the conversion of plasma angular momentum to directed linear momentum in the diverging applied magnetic field. Steady-state MPD thrusters have been operated at power levels from 10-600 kW, and pulsed quasi-steady devices have been operated from kilowatts to megawatts of power.⁴⁹ Specific impulse values are typically on the order of a few thousand seconds, with thruster efficiencies of 20-30%. Pulsed MPD thrusters flown on the Japanese MS-T4 spacecraft produced I_{sp} values around 2500 s with instantaneous efficiencies of 22%. The thruster accumulated over 400 firings during 5 hours of operation, successfully demonstrating quasi-steady MPD operation in a space environment. High power MPD thrusters were also used as plasma sources on the Space Experiment with Particle Accelerator (SEPAC) space shuttle tests, which evaluated spacecraft charging effects.

Recent specific impulse values exceeding 5000 s with efficiencies greater than 50% have been reported for high power MPD thrusters using lithium⁴⁹ and hydrogen⁵⁰ propellants. Lithium is a condensable propellant, however, and may not be appropriate for auxiliary propulsion applications where spacecraft surfaces might be coated or contaminated with propellant backflow. The preliminary performance measurements obtained with hydrogen may have included trace amounts of eroded insulator material, which could surreptitiously contribute to the thrust and raise the inferred specific impulse.⁵¹ Additional thruster performance measurements with hydrogen and deuterium propellants and a careful examination of erosion products are planned.⁵¹

In deference to near-term space power constraints, a recent system analysis⁵² evaluated the potential performance of high power pulsed MPD thrusters operated at average powers of 10-40 kW. Results of the study indicate that substantial mass savings can be obtained for LEO-GEO transfer missions with payloads of 1000-2000 kg, reducing both launch mass and associated launch costs. Although pulsed MPD thrusters are still developmental, the study suggests that pulsed MPD thrusters may offer significant near-term benefits for orbital transfer applications.

A variety of other concepts exist which may have far-term benefits for primary and auxiliary propulsion. The *pulsed inductive thruster* (PIT) uses pulsed electric currents in a flat spiral coil to create transient

magnetic fields, which in turn create strong electric fields near the coil surface. The electric fields ionize a gas propellant injected over the coil surface, and the interaction of the coil current with an induced plasma current accelerates the ionized propellant away from the coil surface. Specific impulse values of 4000-8000 s at efficiencies exceeding 50% have been reported for ammonia propellants.⁵³ Current PIT devices operate at high average powers, and efforts must be made to evaluate thruster performance at average power levels more suitable for near-term space applications. Other advanced propulsion concepts such as the *microwave electrothermal thruster*⁵⁴ (MET) and the *helicon wave plasma thruster*,⁵⁵ are actively being developed in the 10-20 kW power range, and promise efficient operation at specific impulse values of interest. Far-term propulsion concepts such as *laser sustained plasma thrusters*⁵⁶ and *laser thermal thrusters*⁵⁷ have been analyzed and experimentally evaluated at various power levels with a number of propellants. Specific impulse values up to a few thousand seconds have been achieved with efficient laser power coupling to the propellant or to a thermal heat exchanger. Although significant technical issues remain to bring each of these advanced concepts to fruition, their continued development may one day provide substantial benefits for auxiliary and primary space propulsion applications.

Technology Summary.

The match between available laser technology and photovoltaic cell technology is not perfect, but sufficient overlap exists to suggest that ground-based laser beaming can be used with current array technologies to achieve conversion efficiencies greater than those available with solar illumination at similar intensities. Higher array efficiencies allow a reduction in the array mass required for a given power level, reducing the total mass of the spacecraft. The use of auxiliary electric propulsion reduces the propellant mass required for a given mission or application, allowing a further reduction in the total spacecraft mass or providing longer operational lifetimes for the same propellant mass.

Possible laser transmitter-photovoltaic receiver combinations include dye lasers, pumped by copper vapor lasers and tuned to the optimum wavelengths for either silicon or gallium arsenide cells, or Nd:YAG lasers operated in concert with light trapping or high temperature silicon cells. Near-term improvements in

photovoltaic materials, such as CuInSe₂, or the development of kW-class semiconductor diode laser arrays, can further enhance the efficient coupling between ground-based lasers and spaceborne photovoltaic receivers. Available electric propulsion systems include hydrazine resistojets, hydrazine arcjets, pulsed plasma thrusters, stationary plasma thrusters, and derated ion engines, with pulsed MPD thrusters a near-term option. The addition of adaptive optics, which have the demonstrated capability to propagate nearly diffraction-limited laser beams through the atmosphere, completes the list of available technologies required for ground-based laser power beaming for space propulsion applications.

Baseline Technologies.

To facilitate the evaluation of low power ground-based laser beaming applications, the following baseline technologies will be assumed. The ground-based laser system consists of a coherently coupled set of copper vapor laser-pumped dye lasers, tuned to an appropriate atmospheric transmission band at a wavelength suitable for photovoltaic conversion by GaAs cells. To minimize the required technology stretch, the combined laser output power is limited to 5 kW. Based on the laser cost estimates outlined above, the cost of a 5-kW laser system is on the order of \$1-2 million, with probable additional yearly maintenance costs of around \$100-200 thousand (excluding personnel and other operating costs). The beams are assumed to be coherently combined to create a single, 1-m radius laser beam. Significantly smaller initial beam radii will suffer from large diffractive spreading at distances of interest, and significantly larger beam radii may stress the mechanical ability of the ground based laser optics system to follow a rapidly moving satellite in LEO.

Beam expansion optics are used in concert with a deformable mirror adaptive optic system to propagate a nearly-diffraction limited beam through the atmosphere. A return signal for the adaptive optics is provided by either a retroreflective array placed on a satellite boom at the correct point-ahead distance, or by artificial guide stars produced by laser illumination of the atmosphere. In the latter case, a retroreflector must still be attached to the spacecraft body to provide correct wavefront tilt information for the adaptive optics.

The cost of a 241-actuator adaptive optics system for a 2.5 m diameter telescope (beam expander) is estimated at \$3.5 million.³¹ Additional optics, posi-

tion control, satellite tracking systems, ground facilities, and other contingency costs could easily add an additional \$5 million to the initial facility cost. Including the cost of the 5-kW laser system, the estimated initial cost is around \$10 million per laser ground site. The lasers will need maintenance and occasional replacement, and even autonomous facilities will require personnel for various station functions. Assuming that 15% of the initial site cost per year will be required for maintenance, etc., an additional \$1.5 million per year is budgeted for each ground station. Over a ten year station life, the total construction and operating cost is thus estimated to be around \$25 million per laser ground site.

Power conversion aboard the spacecraft is assumed to be provided by GaAs photovoltaic arrays, with a conversion efficiency of 24% under solar illumination and 50% under laser illumination at an intensity equal to 1-sun, or 1.38 kW/m². A planar rigid panel array is most likely to be used for near-term, low power applications,⁵⁸ and a conservative estimate of 30 kg/kW is used for the total array specific mass. A 500-W hydrazine resistojet, 1-kW hydrazine arcjet, and 1-kW derated ion thruster were chosen to represent available auxiliary electric propulsion systems.

III. LOW POWER APPLICATIONS

Given the components for low power ground-to-space laser transmission and conversion, the following sections provide a first-order look at some potential mission applications and additional issues which must be addressed.

Power Beaming Limitations.

Many of the low power electric propulsion devices outlined above have been advocated for the north-south stationkeeping of satellites in geosynchronous orbit (GEO), 3.6x10⁷ m above the Earth's surface. High power ground-based laser beaming has been suggested as a means to provide an equivalent 1-sun intensity to GEO satellite solar arrays during eclipse periods, eliminating the need for onboard storage batteries.²¹ The laser intensity (I) at the receiver is given by the ground-based laser power (P_L) divided by the spot area at the receiver (r_{spot}²):

$$I = \frac{P_L}{\pi r_{spot}^2} \quad (\text{W/m}^2) \quad (6)$$

The spot radius is given by Equation 1, and the two

equations can be combined to determine the laser power necessary to provide a given intensity for an initial beam radius r₀, laser wavelength λ, and beam propagation distance Z:

$$P_L = \frac{\pi (0.61 Z \lambda)^2 I}{r_0^2} \quad (\text{W}) \quad (7)$$

Figure 10 displays a log-log plot of the laser power required to maintain an equivalent 1-sun intensity of 1.38 kW/m² as a function of propagation distance for the baseline beam radius of 1 m and a laser wavelength of 850 nm, which roughly corresponds to the peak wavelength for efficient conversion by a GaAs array. To provide an equivalent 1-sun intensity at GEO requires a ground-based laser power of 1.5 MW, which is considerably beyond the capabilities of the near-term lasers considered in this study. A 10-m diameter adaptive optic system has been suggested for laser power beaming to the moon;²⁴ if such a system could be built, the minimum laser power required to provide a 1-sun intensity at GEO would be 60 kW, still beyond current laser capabilities. The baseline 5-kW laser operating at 850 nm would require an incredible initial beam diameter of 35 m to provide an equivalent 1-sun intensity at GEO, and the mammoth adaptive optics required to provide diffraction-limited propagation for such a large beam are beyond the capabilities of near-term or envisioned technology. The power required for a given intensity decreases as a function of λ², but the range of useful laser wavelengths are constrained by atmospheric transmission and photovoltaic array conversion efficiency considerations to around 600-900 nm (Figures 4 and 6). Reasonable changes in initial beam radius and laser operating wavelength will not significantly impact the required laser power, and laser beaming to GEO is not a practical application for the near-term, ground-based, low power laser systems considered in this paper.

Power Beaming to LEO.

Shown in Figure 10 is a horizontal line delineating the baseline 5-kW laser power assumed for this study. At this power level, a diffraction-limited laser beam at a wavelength of 850 nm and an initial radius of 1 m can provide an equivalent 1-sun intensity out to an orbital altitude of around 2000 km. If the adaptive optics used to propagate the beam through the atmosphere cannot provide diffraction-limited performance, the maximum distance at which the 5-kW laser can maintain a 1-sun intensity can be maintained will be decreased. Because the intensity is inversely propor-

tional to the square of the spot size (Equation 6). a factor of two increase in spot size requires a factor of four increase in laser power to maintain the same intensity at a given distance. The spot size is linearly proportional to the propagation distance (Equation 1), hence a factor of two increase in spot size yields the same intensity for a given laser power level at half the original propagation distance. For the baselined power level of 5-kW, diffraction-limited performance will generate a 1-sun intensity out to 2000 km. If the system operates at twice the diffraction limit, the maximum propagation distance to maintain a 1-sun intensity is cut to 1000 km, still within the range of most LEO satellite applications.

Figure 11 shows the maximum possible illumination time per orbit as a function of orbital altitude for ground station viewing angles of $\pm 45^\circ$ and $\pm 60^\circ$ from zenith. The displayed illumination times assume that the satellite trajectories pass directly over the stations. The illumination time per orbit will be reduced by the angle cosine for trajectories which do not pass directly overhead. For a satellite orbit of 1000 km and a conservative viewing angle of $\pm 45^\circ$, the maximum illumination time is approximately 153 seconds for each pass over the laser ground site. At 2000 km, the maximum illumination time for $\pm 45^\circ$ is extended to roughly 325 seconds per site. Longer illumination times can be obtained for viewing angles of $\pm 60^\circ$, but beaming through such low angles in the atmosphere significantly degrades the compensation ability of the adaptive optics.

Equation 5 can be rearranged to solve for the delta-V provided by expending a propellant mass M_p at a given I_{sp} :

$$\Delta V = - (g \cdot I_{sp}) \ln[1 - M_p/M_0] \quad (\text{m/s}) \quad (8)$$

where M_0 is the initial spacecraft mass and g is the acceleration due to gravity (9.8 m/s^2). The propellant mass expelled per illumination period is given by the product of the illumination time and the thruster mass flow rate. Figure 12 shows the maximum delta-V provided per illumination period for a 500 kg satellite as a function of orbital altitude for the baseline 500-W resistojet, 1-kW arcjet, and 1-kW derated ion thruster. The hydrazine resistojet is assumed to provide an I_{sp} of 300s at a mass flow rate of $1.16 \times 10^{-4} \text{ kg/s}$. The hydrazine arcjet provides an I_{sp} of 450 s at a mass flow rate of $3.73 \times 10^{-5} \text{ kg/s}$, and the derated ion thruster provides an I_{sp} of 1500 s at a xenon mass flow rate of $3.74 \times 10^{-6} \text{ kg/s}$. Because of the limited illumination times (Figure 11), devices with lower

specific impulse and higher propellant mass flow are able to deliver higher incremental velocity changes during each illumination period. Fewer illumination periods are required for the resistojet than for the arcjet or derated ion thruster, potentially reducing the number of ground-based laser stations. The resistojet expends more propellant mass during a given illumination period, however, and the reduced number of laser ground sites is purchased at the cost of more rapid propellant depletion. This suggests a trade-off between the number and associated cost of the laser ground sites necessary to illuminate a satellite to provide a given delta-V, and the potential commercial return of the satellite as a function of its extended time in orbit. These issues are evaluated in more detail below.

Commercial Benefits.

The benefits of using solar-powered electric propulsion versus lower- I_{sp} auxiliary chemical systems are well documented.⁵⁹ The more efficient use of propellant at high specific impulse (Equation 5) allows the total spacecraft mass to be reduced for a given mission, yielding significant savings in launch vehicle costs. A further reduction in mass might be obtained using laser illumination of the solar arrays to power the electric propulsion systems. The higher conversion efficiencies obtained under laser illumination allow the same total power to be generated for a given propulsion system using a smaller photovoltaic array mass. For a given satellite launch mass, the reduction in solar array mass could allow more propellant to be carried, extending the satellite's operational life in orbit. For commercial satellites, extending the life without increasing the total mass (and associated launch costs) enhances the revenue generating capacity of the satellite. The additional revenue must be balanced against the cost of building and maintaining the laser ground stations for the laser system to be of commercial interest.

Communication satellites generate revenue based on the number of transponders they carry. Typical U.S. domestic communication satellites carry up to 24 transponders,^{60,61} with each transponder capable of generating revenues of approximately \$1.5 million per year.⁶¹ Satellite lifetimes are generally 10-12 years.⁶⁰ with operating costs typically less than \$1 million per year per satellite.⁶² Assuming full transponder usage, a 24-transponder satellite is capable of generating a potential revenue on the order of \$35 million/year, or \$350-420 million over the expected lifetime of the satellite. Typical satellite construction and launch

costs are around \$100 million for a 24 transponder satellite,⁶¹ corresponding to a net profit on the order of \$250-300 million per satellite.

Average payload power for 24 transponders and attendant housekeeping duties, battery charging requirements, etc., is generally around 500 W.^{60,62} Resistance losses and contingency power requirements may increase the primary power requirements to around 750 W, which can be supplied by a 22.5 kg GaAs rigid planar solar array. In addition to the payload power requirements, the solar array must provide additional power for the auxiliary electric propulsion system. A 500-W resistojet would require an additional solar array mass of 15 kg, which would increase to 30 kg for a 1-kW arcjet or derated ion thruster. The potential benefit of laser power beaming accrues from the doubling of the photovoltaic array efficiencies under illumination at the proper laser wavelength. Ground-based laser power cannot be continuously supplied to a satellite in LEO, and the array mass required for payload power would still have to be carried along. However, doubling the efficiency of the array with laser illumination allows the array mass required for auxiliary propulsion to be halved, from 15 kg to 7.5 kg for the resistojet and from 30 kg to 15 kg for the arcjet and derated ion thruster. For a given initial satellite mass at launch, the mass saved by reducing the solar array mass could be put toward propellant mass, which could then be used to extend the life and revenue generating capability of the communication satellite.

For example, consider a 500 kg communication satellite in an 800 km low Earth polar orbit, typical of proposed constellation satellite masses and altitudes.⁶³ At 800 km, the maximum satellite illumination time is 120 seconds per laser ground site. Figure 13 shows the required number of illumination periods per day as a function of yearly delta-V for each of the baselined electric propulsion systems. As expected from Figure 12, the resistojet requires the fewest illumination periods to provide a given delta-V, while the high- I_{sp} , low mass flow rate derated ion thruster requires substantially more illumination periods. To provide a yearly delta-V of 50 m/s, which is more than adequate for drag makeup at 800 km,⁶⁴ the resistojet requires 204 seconds of laser illumination each day, or 1.7 illumination periods/day; the arcjet requires 3.4 illumination periods/day, and the derated ion thruster requires 10.3 illumination periods/day. For a yearly delta-V of 500 m/s, adequate for drag makeup and limited orbital maneuvering, the resistojet requires 16.5 illuminations/day, the arcjet requires

34.2 illumination periods/day, and the derated ion thruster requires 103 illumination periods/day.

Assuming a conservative scenario in which a given ground site can only see the satellite once per day, the number of illumination periods/day required to provide a given delta-V corresponds to the required number of ground sites. Figure 13 indicates that the resistojet, and to a lesser extent the arcjet, can provide fairly significant yearly delta-V's for a reasonable number of ground stations, while the derated ion thruster would require a proliferated system of ground stations to provide yearly delta-V's in excess of a few hundred m/s. However, the lower mass flow rates associated with the higher specific impulse derated ion thruster provide it an advantage in prolonging the satellite life in orbit, and the associated benefit of generating additional revenue which could compensate for the cost of additional ground stations. In addition, a proliferated number of ground stations could be used to illuminate more than one satellite per day, amortizing the cost of the ground stations.

Figure 14 displays the extended satellite life for a 500 kg satellite in an 800 km polar orbit as a function of yearly delta-V for each of the baselined laser electric propulsion systems. Recall that the extended life is achieved by reducing the solar array mass necessary to power the laser electric propulsion system compared to the array mass required for solar power alone, allowing extra propellant mass to be carried without increasing the total spacecraft mass. The 500-W resistojet reduced the array mass by 7.5 kg, and this mass provided the 7.5 kg of extra propellant used to prolong the orbital life compared to a 500 kg satellite, using the same 500-W resistojet, but powered only with solar radiation. Due to the higher power levels, the 1-kW arcjet and 1-kW derated ion thruster each reduce the solar array mass by 15 kg, which allows a 15 kg increase in the propellant mass. The higher I_{sp} ion thruster uses less propellant to achieve a given delta-V, and the extra 15 kg of propellant provides a longer orbital life extension than achieved with the arcjet.

It may appear that operating the 500-W resistojet with less total propellant than the higher power ion or arcjet is an unfair restriction. Although 500-W is typically the limit for long-life resistojet operation, a test-bed 1-kW hydrazine resistojet has been demonstrated at an I_{sp} of 310 s and a mass flow rate of 2.93×10^{-4} kg/s. Because the I_{sp} is nearly the same as the 500-W resistojet, the approximate number of illumination periods/day required to achieve a yearly

delta-V can be obtained from Figure 13. For a 500 kg spacecraft at 800 km, the resistojet must fire for approximately 204 s/day, for a total propellant mass expenditure of 3.5×10^2 kg/day. For an extra propellant loading of 15 kg, the 1-kW resistojet can extend the satellite life in orbit for an additional 1.2 years, which is only 1.3 times longer than the 500-W resistojet using only 7.5 kg of extra propellant and significantly less than the possible life extensions achieved with the 1-kW arcjet and 1-kW derated ion thruster. For a yearly delta-V requirement of 500 m/s, the 1-kW resistojet with 15 kg of extra propellant can extend the satellite life only 26 days, compared to 33 days for the 500-W resistojet. The use of higher power resistojets, operating at concomitantly higher flow rates, does not appear to significantly extend satellite lifetimes over those achieved with proven, long-life 500-W resistojet technology.

The right side of Figure 14 displays the additional revenue generated by a 500 kg commercial satellite in a 800 km polar orbit due to extended orbital life. The satellite is assumed to have 24 transponders, with each operating at only half capacity. As noted above, each transponder can generate approximately \$1.5 million per year at full capacity, hence a satellite with 24 transponders operating at half capacity can generate a potential revenue of \$18 million per year. At full capacity, the extra revenue generated per year would be twice the values shown in the figure. The use of ground-based laser power for electric propulsion allows the satellite life to be extended past the life achieved using solar powered electric propulsion alone, generating the additional revenue shown in the Figure 14. For fairly low delta-V requirements, consistent with yearly drag makeup, the extra revenue can be quite substantial. If the satellite is required to perform orbital maneuvers requiring a delta-V's of hundreds of meters per second per year, the extra life in orbit and associated generated revenue may be inconsequential, and the mission might just as well be performed with solar powered electric propulsion.

As noted previously, Figure 13 can be used to estimate the number of laser ground stations required to provide a given yearly delta-V for each of the baselined propulsion systems. Under the conservative assumption that a single ground site can only illuminate a given satellite once per day. The total cost of a laser ground station is given by the construction cost and total operating cost. Assuming that a solar powered electric propulsion system can

maintain the 500 kg communication satellite in the 800 km polar orbit for 10 years, Figure 14 displays the additional lifetime beyond the 10 year period that the laser powered electric propulsion system can keep the satellite in orbit. The total cost of the laser ground station is thus given by:

$$C_{gs} = \$10M + (10+N)*\$1.5M/year \quad (9)$$

where C_{gs} is the total station cost, \$10M is the assumed construction cost. N is the number of years the laser illuminated electric propulsion system extends the satellite life past the 10 years available with solar powered electric propulsion, and \$1.5 is the estimated yearly maintenance cost of the station. For example, if the laser electric propulsion system extends the satellite life an additional 2 years, the total station cost is estimated to be \$28 million. The laser ground station cost must be multiplied by the number of stations required to provide the required yearly delta-V. Assume the arcjet is used to provide a yearly delta-V of 100 m/s to a 500 kg communication satellite in an 800 km polar orbit. Figure 13 shows that seven laser ground stations are required, assuming that each ground station illuminates the satellite once per day. Figure 14 shows that the satellite life is extended for roughly 1.3 years, and from Equation 9 the cost of a single ground station operating for 11.3 years is around \$27 million dollars. Multiplying this amount by seven operational stations yields a total investment of around \$190 million. This total ground station cost must be covered by the extra commercial satellite revenue for the laser beaming concept to be competitive. For example, using a laser powered arcjet to provide a yearly delta-V of 100 m/s, Figure 14 shows that a 24 transponder satellite operating at half capacity will generate approximately \$24 million in extra revenue. For the laser system to reach economic breakeven, at least eight such satellites must each be illuminated by the seven laser ground stations once per day. Hence for delta-V's of interest, multiple satellites must be illuminated by each of the ground-based laser sites for the concept to be financially competitive with solar electric auxiliary propulsion.

Figure 15 displays the estimated number of spacecraft which must be illuminated by the laser ground stations, as a function of delta-V per year for each of the baselined electric propulsion systems, for the system to reach financial breakeven. This figure should be read together with Figure 13, which indicates the number of ground stations required to

provide a given yearly delta-V under the assumed requirement of 1 ground site per illumination period. Even with the relatively conservative estimates used for commercial satellite revenue generation, the total number of satellites required for the system to reach financial breakeven falls well below the total number of spacecraft generally proposed to populate communication satellite constellations in similar orbits.⁶³

For reasons noted earlier, the laser illuminated resistojet requires significantly more satellite targets than either the arcjet or derated ion thruster. Of particular interest, Figure 15 shows that the 1-kW arcjet and 1-kW derated ion thruster must both illuminate about the same number of spacecraft for the laser systems to reach breakeven, even though the ion propulsion system requires significantly more ground stations (Figure 13). For example, Figures 13 and 15 show that to provide a 100 m/s delta-V with laser illuminated arcjets requires 7 ground stations, each illuminating 8 satellites once per day. The laser illuminated derated ion thrusters require 21 ground stations, each of which must also illuminate 8 satellites once per day. The laser illuminated ion thrusters provide longer extensions of the satellite lifetimes, allowing the cost of operating the more numerous ground stations to be recouped.

Locating 7 ground sites such that each site sees 8 satellites once per day may be less difficult than trying to locate 21 ground sites, each of which must also see 8 satellites once per day. However, the 21 ground sites may be able to target more satellites in a multiple satellite constellation. Either way, the use of the minimum number of ground stations to illuminate more than the minimum number of satellites required for breakeven will generate a return on the laser station investment. Detailed satellite ground track analyses and site placement surveys should be undertaken to determine the optimum number of ground stations for a given satellite constellation. Probable locations for laser ground stations operating in concert with polar orbiting satellites are near the Earth's polar regions, where multiple satellite orbits may be accessed. Weather concerns and limited access may pose additional problems, which must be evaluated. A veritable cornucopia of illumination scenarios exist, each of which must correlate satellite orbits, delta-V requirements, electric propulsion performance, and laser ground station placement. The parametric exploration of these multiple scenarios is left as a future exercise.

Additional Considerations.

The previous examples assumed a 500 kg satellite mass in an 800 km orbit. As a consequence of Equation 5, if the satellite mass were to be increased, the number of illumination periods required to provide a given delta-V using the same baseline electric propulsion systems would also increase. For a 1000 kg satellite, the number of illumination periods/day shown in Figure 13 would double. Under the conservative assumption that each laser site can only illuminate the satellite once per day, the required number of laser ground sites would also double, increasing the total ground system cost. If the satellite mass were kept at 500 kg but the orbital altitude were reduced to 400 km, the associated decrease in the available illumination time (Figure 11) would again raise the number of ground stations required to maintain a given delta-V at the lower orbit. Longer illumination times are available at higher orbits, and the number of ground stations may be reduced to make the system more economically competitive. Alternative illumination scenarios, such as basing the lasers on high altitude aircraft, could reduce the need for adaptive optics as well as lengthen the illumination time per satellite. In all such scenarios, the orientation of the solar arrays with respect to the laser ground or air stations must be taken into account; the laser won't be of much use if the arrays can't see it.

Other factors must be taken into account to ascertain the utility of ground-based laser power beaming to LEO. Although rigid panel photovoltaic arrays are most likely to be flown in the near term, progress is continuing on photovoltaic arrays of lower specific mass. The APSA panels discussed earlier are projected to have specific masses of around 7.2 kg/kW. Doubling the efficiency of 1-kW array under laser illumination would only decrease the array mass by 3.5 kg. The life extensions discussed in the previous section, based on 15 kg of extra propellant, would be reduced by roughly a factor of 4. The extra revenue generated would be significantly diminished, and the required number of satellites to be illuminated just for breakeven would increase to the point of making the ground based laser system impractical.

Low specific mass batteries capable of powering the electric propulsion systems for the required time periods would also obviate the utility of a proliferated ground-based laser system. Nickel hydrogen batteries

with specific energies approaching 32 W-hr/kg have been used for geostationary satellite applications, and are currently undergoing testing for LEO satellite applications.⁶⁵ Such batteries, or derivatives thereof, could competitively supply the necessary power for propulsion without resorting to the complexity of multiple laser ground sites.

IV. CONCLUDING REMARKS

An extensive review of commercial and near-term laser systems, photovoltaic arrays, and adaptive optics indicates that low power ground-based laser illumination of photovoltaic arrays in LEO is presently feasible. Approximately 5-kW of power at an equivalent 1-sun intensity (1.38 kW/m²) can be propagated to an approximate orbital distance of 2000 km using coherently coupled dye lasers and diffraction-limited adaptive optics. The efficiency of photovoltaic arrays can double under laser illumination of the proper wavelength, allowing a reduction in the solar array mass required for auxiliary electric propulsion. The reduced array mass allows extra propellant to be carried without increasing the satellite launch mass. The additional propellant provides an extended orbital lifetime, which can provide additional revenue for commercial satellite owners.

A preliminary analysis was performed to estimate the commercial viability of a ground-based laser system acting in concert with a 500-W resistojet, a 1-kW arcjet, and a 1-kW derated ion thruster. The assumed specific impulse values for each thruster were 300 s, 450 s, and 1500 s, respectively. The lower I_{sp} devices required less illumination time to achieve a given delta-V, but expended more propellant mass than the higher I_{sp} thrusters. Assuming a single ground station could illuminate a satellite once per day, the lower I_{sp} devices required fewer ground stations to achieve a given delta-V, but their larger propellant expenditure lessened the extended time in orbit.

A trade study comparing the total cost of the laser ground stations required to provide a given delta-V versus the extra revenue generated by extending the useful life of a number of communication satellite was performed. Using conservative cost values, the initial cost per ground-based laser facility was estimated to be \$10 million, with an additional \$1.5 million per year per facility in maintenance and operating expenses. Each communication satellite was assumed to carry 24 transponders operating at

half capacity, generating a total of \$18 million per year per satellite in additional revenue. A solar powered electric propulsion satellite was assumed to have an orbital life of 10 years, which was used as a baseline to gauge the performance of the laser illuminated satellites.

The estimated total cost of the laser ground stations included the initial cost of \$10 million per facility, plus \$15 million per facility in operating and maintenance costs over the baseline 10 year satellite lifetime and \$1.5 million per facility per year for each year of extended satellite life. The extra revenue generated by extending the satellite lifetimes using laser electric propulsion had to cover the full cost of the laser ground facilities for the laser system to be competitive with solar powered electric propulsion. The number of satellites required for the laser electric propulsion system to reach breakeven was substantially less than the typical number of satellites proposed for communication constellations, indicating that the ground-based laser system could be commercially viable.

A variety of issues remain to be addressed. Ground track analyses and site location studies should be performed to determine optimal satellite orbits and ground station placement. Severe weather at critical site locations could require additional ground sites to be built for redundancy, diminishing the economic competitiveness of the system. Anticipated near-term developments in low specific mass solar arrays and high energy density batteries for LEO applications would diminish any competitive advantage currently held by low power, ground-based laser concepts, obviating the need for such systems to be built.

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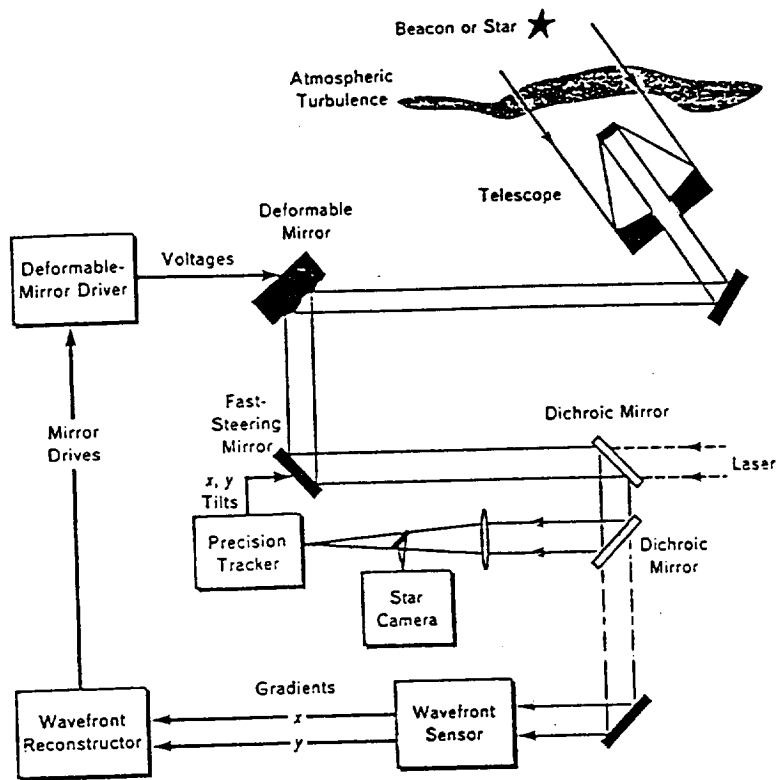


Figure 1. Adaptive optics system for astronomy.¹⁷

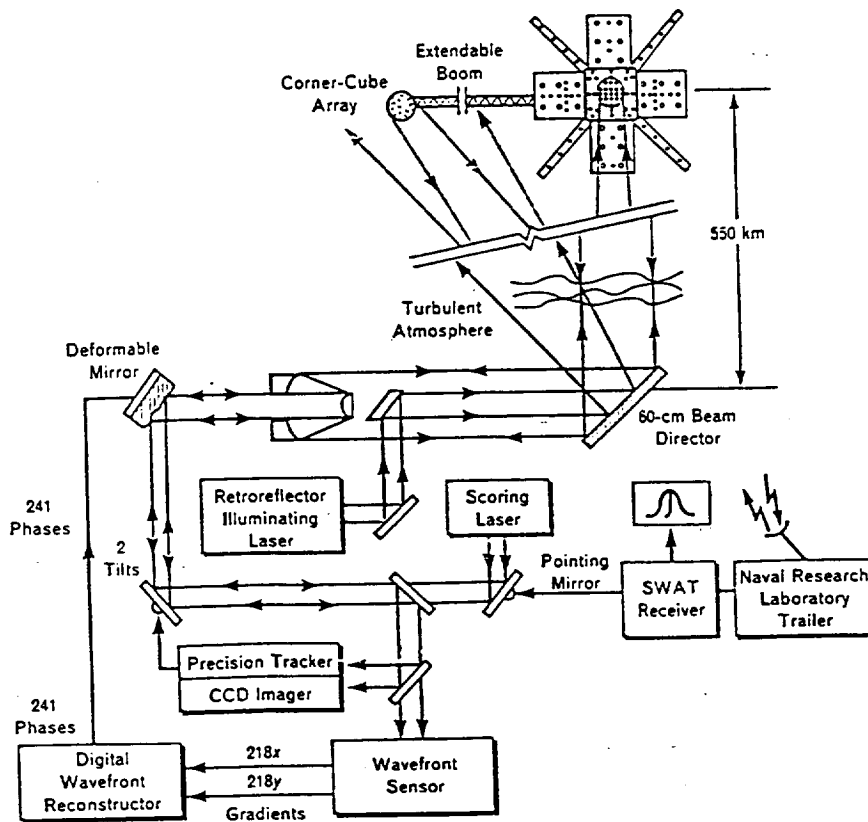


Figure 2. Adaptive optics compensation using satellite retroreflectors for ground-based laser power beaming to spacecraft in LEO.²⁰

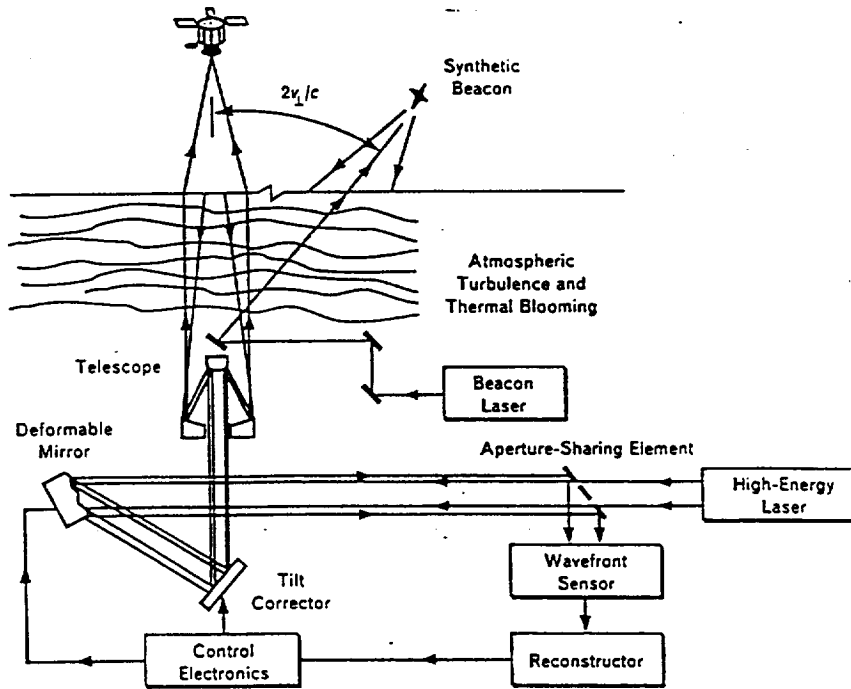


Figure 3. Adaptive optics compensation using laser generated synthetic beacons for ground-based laser power beaming to spacecraft in LEO.¹⁹

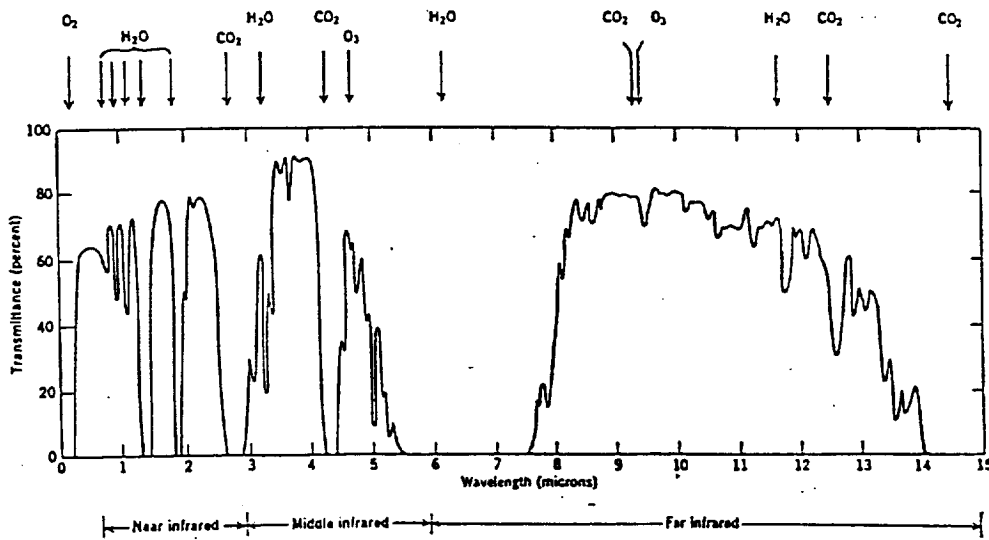


Figure 4. Atmospheric transmittance at 0-15 μm .²⁵

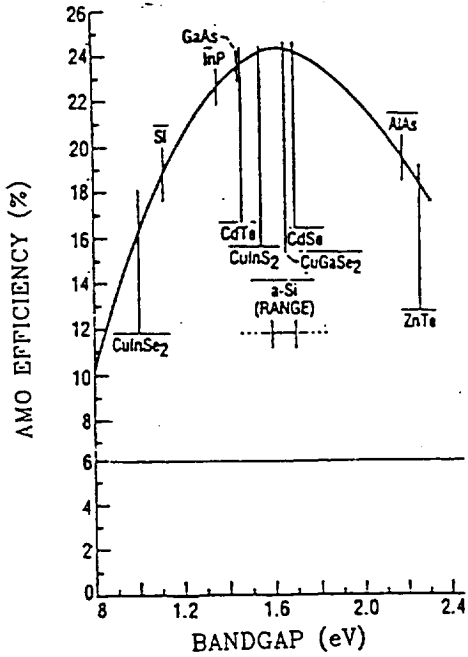
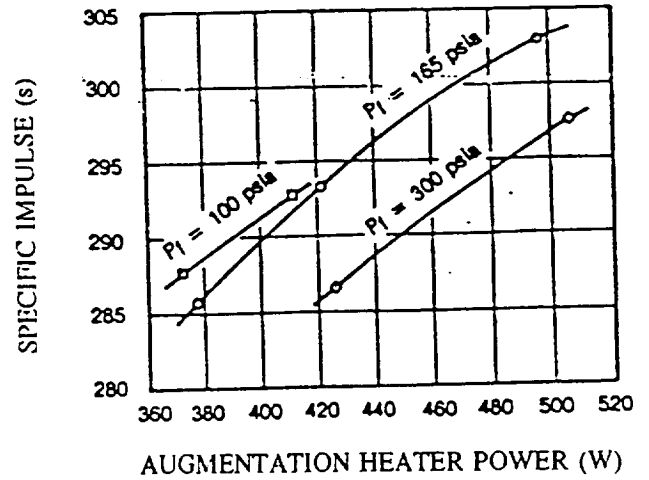


Figure 5. Efficiency of photovoltaic materials under solar illumination (air mass zero).⁶⁶



(7a)

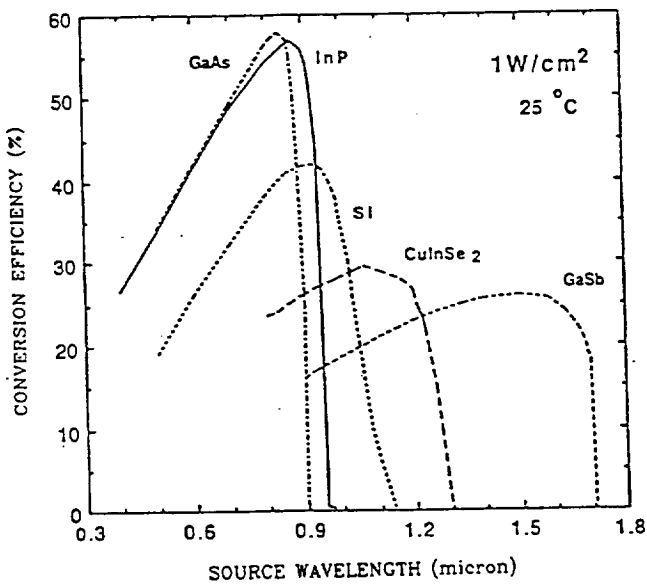
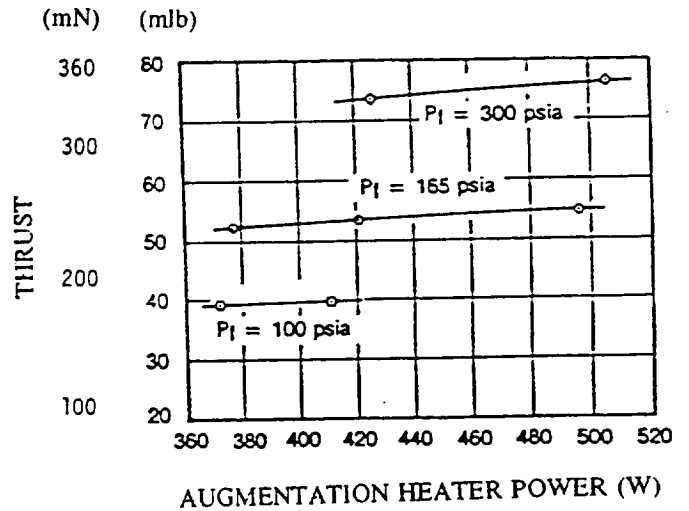


Figure 6. Conversion efficiency of photovoltaic materials under monochromatic illumination.²²



(7b)

Figure 7. Augmented catalytic thruster (a) specific impulse and (b) thrust vs. heater power for various feed pressures.⁴¹

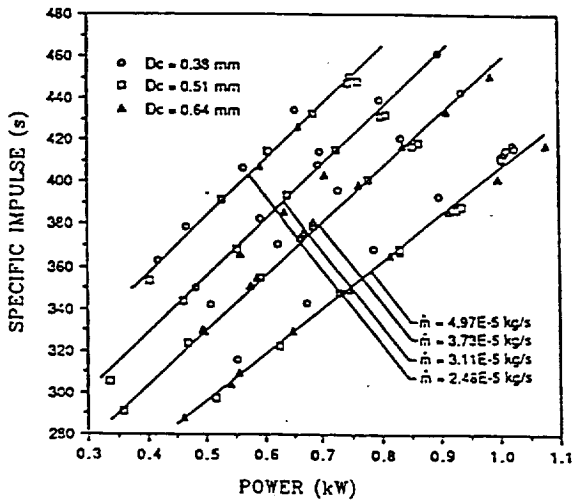


Figure 8. Hydrazine arcjet specific impulse vs. power for various mass flow rates and constrictor diameters.⁴²

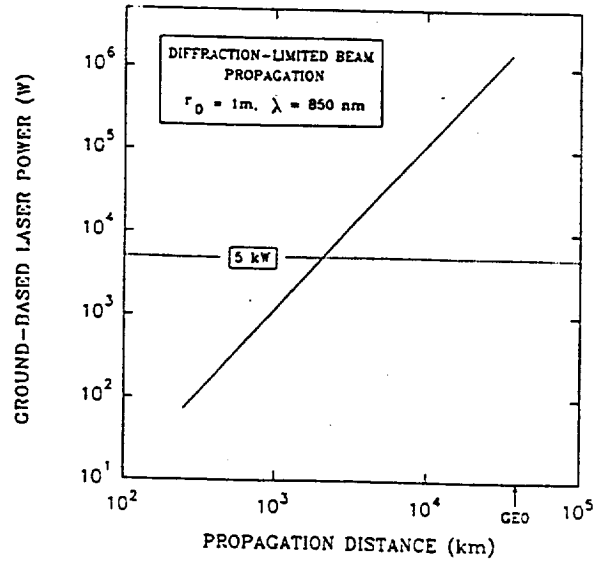
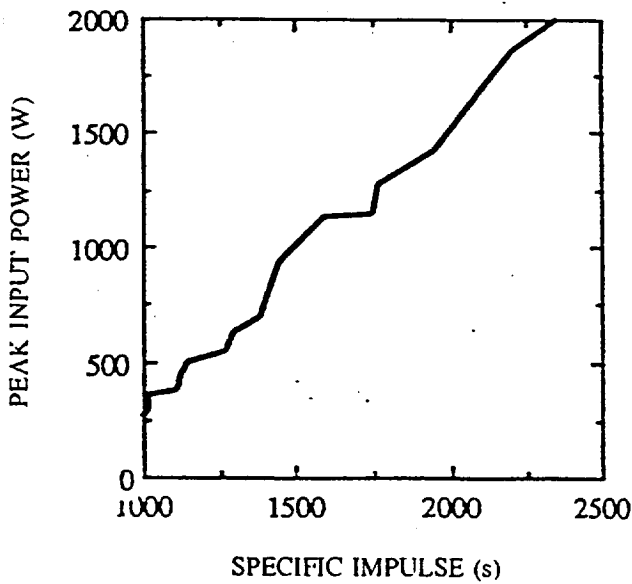
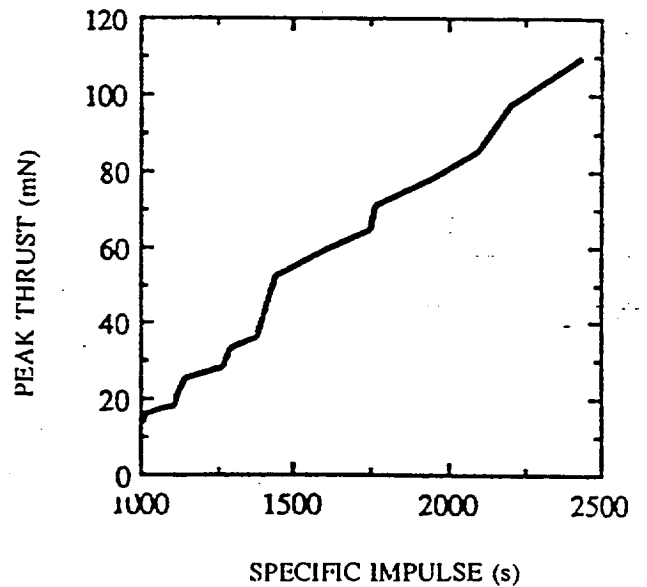


Figure 10. Diffraction-limited ground-based laser power required to sustain equivalent 1-sun intensity vs propagation distance. Initial beam radius = 1 m, laser wavelength = 850 nm.



(a)



(b)

Figure 9. Derated 30-cm xenon ion thruster (a) specific impulse vs. power and (b) peak thrust as a function of specific impulse.⁴⁸

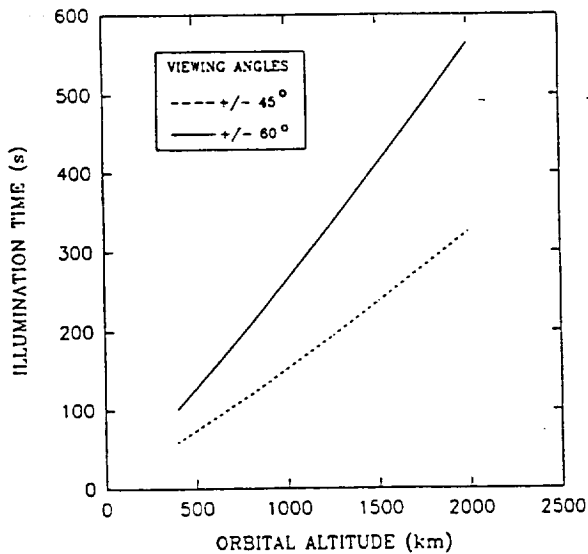


Figure 11. Maximum illumination time per site vs. spacecraft orbital altitude for viewing angles of $\pm 45^\circ$ and $\pm 60^\circ$ from zenith.

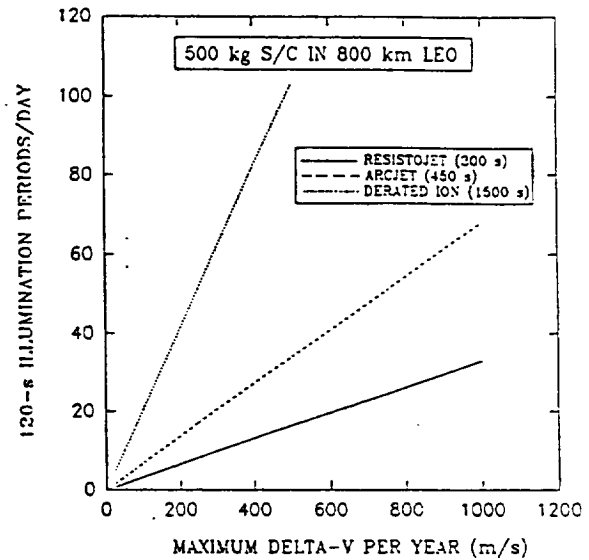


Figure 13. Maximum # of illumination periods per day required to achieve a given delta-V per year for each of the laser-powered electric propulsion systems assuming an initial spacecraft mass of 500 kg at an assumed orbital altitude of 800 km.

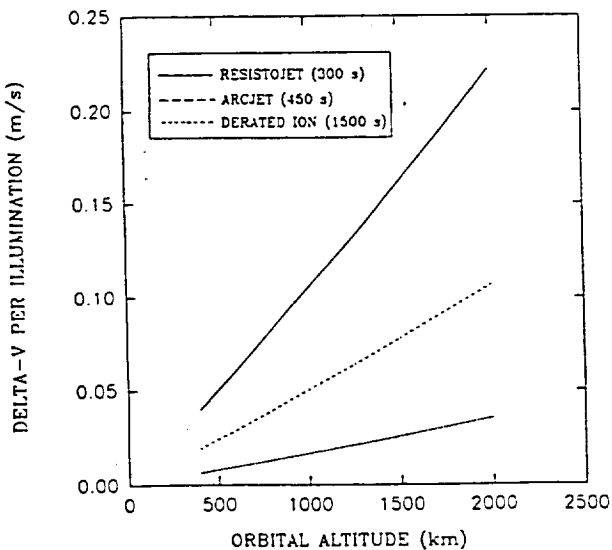


Figure 12. Maximum delta-V per illumination achieved by the baselined laser-powered electric propulsion systems as a function of spacecraft orbital altitude.

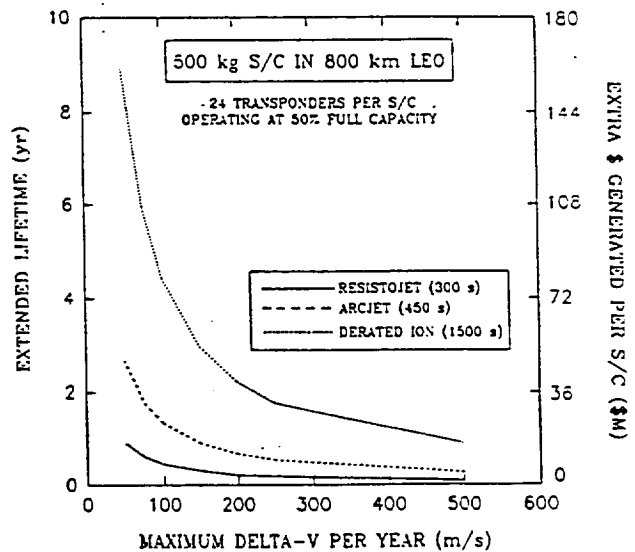


Figure 14. 500 kg satellite lifetime extension in 800 km orbit and corresponding increase in revenue generated per spacecraft as a function of delta-V.

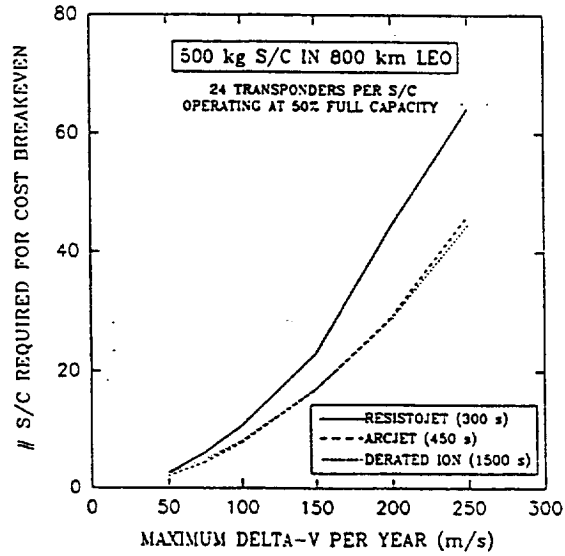


Figure 15. Estimated number of communication satellites which must be illuminated in an 800 km orbit as a function of yearly delta-V requirement for the ground-based laser system to reach cost breakeven.

NOTES

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13. ABSTRACT (Maximum 200 words) A preliminary evaluation of low power, ground-based laser powered electric propulsion systems is presented. A review of available and near-term laser, photovoltaic, and adaptive optic systems indicates that approximately 5-kW of ground-based laser power can be delivered at an equivalent 1-sun intensity to an orbit of approximately 2000 km. Laser illumination at the proper wavelength can double photovoltaic array conversion efficiencies compared to efficiencies obtained with solar illumination at the same intensity, allowing a reduction in array mass. The reduced array mass allows extra propellant to be carried with no penalty in total spacecraft mass. The extra propellant mass can extend the satellite life in orbit, allowing additional revenue to be generated. A trade study using realistic cost estimates and conservative ground station viewing capability was performed to estimate the number of communication satellites which must be illuminated to make a proliferated system of laser ground stations economically attractive. The required number of satellites is typically below that of proposed communication satellite constellations, indicating that low power ground-based laser beaming may be commercially viable. However, near-term advances in low specific mass solar arrays and high energy density batteries for LEO applications would render the ground-based laser system impracticable.				
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