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NASA Contractor Report 190793
IAF-92-0600

Laser Beamed Power: Satellite Demonstration Applications

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August 1992

Prepared for the
43rd Congress of the International Astronautical Federation
sponsored by the International Astronautical Federation,
Washington, D.C., August 28–September 3, 1992

National Aeronautics and
Space Administration

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SATELLITE DEMONSTRATION APPLICATIONS

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Abstract

It is possible to use a ground-based laser to beam light to the solar arrays of orbiting satellites, to a level sufficient to provide all or some of the operating power required. Near-term applications of this technology to providing supplemental power for existing satellites are discussed. Two missions with significant commercial pay-off are supplementing solar power for radiation-degraded arrays, and providing satellite power during eclipse for satellites with failed batteries.

Introduction

Beaming of power by laser from the installations on the surface of the Earth to photovoltaic receivers in space is a technology of considerable interest for many applications [1]. An earlier paper [2] proposed using lasers for eclipse power for communications satellites or other earth-orbiting systems (included as appendix 1 to this report). In this paper it is proposed that a near-term demonstration mission for laser power beaming might be to provide power to existing satellites at or near the end of life due to power system degradation. Such a mission would both demonstrate laser power beaming at a power level that may be achievable with existing technology systems, and also have a large commercial value.

An example case is that of a geosynchronous orbit (GEO) communications satellite near the end of life due to radiation damage of the solar arrays or battery failure.

Geosynchronous Earth orbit satellites are the major portion of commercial space activities. All satellites currently operating in GEO are powered by solar arrays. For operation during eclipse periods, when the Earth shadows the satellite from the sun, a battery system charged by the solar array provides the primary power. The geosynchronous orbit is in eclipse during two 45 day periods centered on the equinoxes, a total of 90 days per year. Eclipse duration is maximum at the equinox, when it reaches 69 minutes, about 5 percent of the orbit [3].

Geosynchronous orbit satellites are designed with all systems having a design life in excess of the fuel depletion design life, which is usually 10 to 15 years. As a result, fuel depletion historically determined the end of life for most commercial communications satellites. The primary fuel use is for north-south station-keeping. Recently one of the authors has developed a technique called "inclined orbit operation" [4], which eliminates north-south station keeping, reducing fuel consumption by 90%. This has had the effect that fuel consumption is no longer the limiting factor for satellite life. This technique is rapidly being adopted worldwide, as the present generation of satellites approach their original end of life date.

The end of life condition for this growing population of communications satellites is now expected to be failure of the power system. The other systems are proving to be unexpectedly robust, with minimal problems once the satellites have reached operational status. Two types of power failure or degradation occur:

(1) Battery failure due to random internal shorts or capacity degradation,
(2) Solar array degradation due to accumulated radiation exposure.

Laser power beaming can be used to offset both types of failure, hence extending the life of a satellite nearly indefinitely.

Solar array degradation reduces the amount of power available, but does not, in general, cause complete failure of a satellite. As the power decreases, transponders must be shut off, reducing the revenue from the satellite proportionally. Laser power could supplement the solar power to increase the power availability back to full power. This would be possible for spin-stabilized satellites, which have non-oriented cylindrical solar arrays. The advantage of using laser power beaming to offset array degradation for a near-term demonstration is that the total power density needed at GEO is low, since laser power is required only to supplement available solar energy. However, this requires near continuous use of the laser (short outages due to clouds can be covered by the battery storage, as long as battery failure has not yet occurred).

Battery failure is typically an abrupt failure, and results in end of life for the satellite. When battery failure occurs, most of these satellites cannot survive for any appreciable time, since fuel is rapidly be consumed to regain the attitude control that would be lost each eclipse day. In addition the customers would not tolerate the repeated outages. Providing power by laser during the eclipse periods will keep the satellite operational and revenue bearing.

The power level required is higher than the array-degradation compensation mission, since most customers will not accept a one-hour transponder outages during eclipse. (Providing housekeeping power only may be acceptable for non-communications satellite types, such as weather satellites, which do not require uninterrupted operation.) This requires the laser power to be high enough to provide nearly full power to the satellite. However, the higher power levels required are offset by relaxed conditions for continuous power, since the eclipse season only lasts for 90 days per year, and power is required for a maximum of 69 minutes per day.

Table 1 shows the required power for a satellite typical of those discussed here. At a bare minimum, housekeeping functions (satellite stabilization, Earth uplink) must be kept operating. This requires roughly 11% of full power for 24 transponder satellites of the type under consideration.

Table 1
Typical power requirements
COMSTAR satellite
(24 C-Band transponders, 28 V power bus)

function	current (A)	power (W)
Housekeeping	2.2	61.6
Transponders		
each transponder	0.7	(16.8)
total		470.4
Battery charging	1.5	42.0
		544.

This is the power used by the satellite. Power produced by the array is higher, and includes losses in power regulation circuitry, resistance loss in wiring, allowance for array degradation and seasonal power variation, and contingency power.

Satellites

Worldwide, 168 communications satellites (counting both K band and C band but not military) are operational in geosynchronous orbit as of the beginning of 1992, with at least another 53 announced as scheduled to be launched between 1992 and 1997. Total U.S. Revenues from communications satellites are about three billion dollars per year.

Typically 20 to 25 new commercial satellites are launched each year, at an investment of about 136 million dollars for a medium sized communications satellite, and near 250 million dollars for a large (*e.g.*, Intelsat VI) satellite.

There are currently 22 satellites which have exceeded design end of life and are continuing in operation into the fuel-saving inclined-orbit mode discussed. Each of these is currently dependant on the continued successful operation of their batteries, which will fail in the next few years. In the next few years, additional satellites reaching end of life will be put into the fuel-saving extended life mode. All of these are candidates for lifetime extension by laser power beaming. The typical size of these satellites is approaching 24 transponders. The revenue generated from a transponder can be \$2M/year. For revenue generated by old satellites, we assume a 50% discount, and thus each C-Band transponder can generate \$1M/year in revenue. The operating costs of these satellites are less than \$1M/satellite per year. Therefore, since these older satellites are already fully depreciated, the economic benefits of laser power beaming to replace failed batteries are enormous, potentially as high as \$500M/year today, if full utilization of the available transponders is achieved, and higher as more satellites reach end of life.

While power beaming to supplement degraded arrays is a less attractive demonstration mission due to the continuous operation requirements for the laser, there are also a number of satellites which could benefit from this mission. Examples of satellites with low power due to solar array degradation include the television satellites BS-2B and BS-3A, and the military navigation satellite Navstar 6. These satellites could be brought back into service using laser power to supplement the solar arrays.

BS-2B and BS-3A are both Japanese direct-to-home broadcast satellites. BS-2B exceeded its five-year design lifetime in 1991, and the solar arrays are degrading [5]. BS-3A had one channel dropped due to an electrical short in the power system which reduced power by 25%, and the effects of solar flare activity in 1991, which further degraded the array [5].

The Navstar 6 geopositioning satellite is still operational eight years after exceeding its four year design life, but has little or no maneuvering fuel left for adjusting its orbit. This satellite series is normally put in a high-sun / low eclipse orbit, but this slowly shifts during the year to a low-sun orbit if periodic orbital adjustments are not made. Due to the relative low power in the current orbit, the satellite is not usable [6].

Example Case: Hipparcos

Communications satellites are not the only candidate targets for use of laser illumination to enhance a failing power system. A highly visible mission which could be done by laser power beaming is to provide eclipse power for the European scientific satellite "HIPPARCOS" (High Precision Parallax Collecting Satellite) [7], an ESA astronometric satellite with a cost of about $300M. It was designed for geosynchronous orbit, but was left in a geosynchronous transfer orbit by a faulty apogee kick motor [8] . Hipparcos thus passes through the radiation belts 4.5 times a day, and so solar array degradation is much higher than planned. Due to precession of the orbital axis, the duration of the eclipse varies. By power load management, Hipparcos will be able to survive until a long eclipse season begins in about four years [9]. At this time the degraded solar arrays will be unable to bring the batteries up to sufficient charge to provide housekeeping power in eclipse, and unrecoverable battery failure will occur. While the original design life of 2.5 years has already been exceeded, in the existing orbit the desired star data is accumulated at a slower rate than planned. It would be desirable to extend the lifetime to accumulate more star sightings. In particular, repeated astrometrical observations of the same star could be used to measure the mass and orbital periods of the planets of nearby stars.

Powering Hipparcos is a significant target mission for several reasons:

1. The satellite can be rescued with application of laser power for only a few weeks, until the eclipse season ends.
2. Laser power is needed only to supplement solar power--full one sun intensity may not be required.
3. It is a very high profile mission-- rescue of an international satellite worth approximately 300 million dollars.
4. It is a mission demonstrating international cooperation, which gives it a high political profile.

There are several difficulties:

1. A program to provide laser beamed power to Hipparcos using a U.S. laser would involve international agreements and cooperation, with all the attendant complexity.
2. The highly eccentric orbit results in very high slew rates at perigee, making it considerably more difficult than a GEO satellite to track.
3. Geosynchronous transfer orbit enters eclipse twice per day, instead of the single eclipse per day encountered by a GEO satellite. Due to the Earth's rotation, some of these orbits will be in less favorable orientations for power beaming than others.

Despite the problems, the potential payoff is high enough that that this should be considered as a candidate mission for power beaming.

System

GENERAL SYSTEM CONSIDERATIONS

A laser power beaming system has four major components: (1) a laser capable of putting out a high average power for a long duration, (2) an adaptive optics system to compensate for distortion of the laser beam as it traverses the Earth's atmosphere, (3) a large optical element to minimize the diffraction of the beam, including a pointing and beam control system, and (4) a photovoltaic receiver on the satellite. This is shown in schematic in figure 1.

For applications to existing satellites, the laser wavelength must be chosen to be compatable with the spectral response of radiation-damaged silicon solar cells, with a peak response near 800 nm, and moderate performance from about 600 to 900 nm. This mission could be a near-term demonstration of laser power utilization on an existing satellite using existing lasers and technology which has been developed for other purposes.

The solar array needed to receive the beamed power is already in place on the satellite. For the battery replacement mission, laser power is required only for periods of less than 70 minutes per day for 90 days out of the year. This allows ample time for laser refurbishment and preventative maintenance.

As the satellite enters eclipse, the laser arrays illuminate the solar panels on the satellite to a level sufficient to provide operating power.

Each ground laser station can successively illuminate several satellites at different longitudes. As one satellite exits the eclipse region, the laser is retargetted to another satellite entering the eclipse. Even if a ground-based laser can scan only an angle of ±45° from the zenith, a single laser station could provide power for five satellites at different longitudes.

Solar Cells

Solar cells in GEO are subject to degradation in power due to trapped radiation and solar flares. Solar arrays are typically oversized in order to provide power under worst-case end of life conditions. Once set up to provide eclipse power, the laser power system described could also be used to provide supplementary power if needed to compensate for radiation damage to the arrays.

Existing communications satellites use silicon solar cells with efficiency ranging between about 12 to 14%. (Gallium arsenide cells, although more efficient, are not in use on currently flying satellites.) This efficiency degrades to under 10% after long exposure to the space radiation environment. The degradation depends on the cell type, the amount of radiation shielding used, and whether the cell is mounted on a deployed array or body-mounted to the satellite. The efficiency increases under laser illumination, since the laser wavelength can be chosen to be near the optimum conversion wavelength (subject to the constraint of atmospheric transparancy).

For example, the peak of the spectral response is typically near 950 nm for undamaged Si solar cells. The efficiency drops rapidly toward zero at longer wavelengths. At 1060 nm, a wavelength of interest for lasers, the efficiency is down by a factor of three or more from the peak. Figure 2 shows a measured spectral response of a conventional silicon solar cell of the type used in 1974, similar to those used on satellites of that era [10]. Without radiation damage, the response is quite linear out to about 950 nm, but drops off rapidly above this value. With radiation damage, the wavelength of peak response decreases to around 700-800 nm.

Near the optimum wavelength, the monochromatic light efficiency can be roughly estimated as double the conversion efficiency for sunlight. More precisely, the efficiency under laser illumination, η_{laser}, can be calculated if the spectral response SR(l) and the short circuit and efficiency under solar illumination are known, by [11]:

$$\eta_{laser} = \eta_{solar} P_{sun} SR(\lambda) / J_{sc} \qquad (1)$$

P_{sun} equals 1370 W/m^2. For silicon cells similar to those on 1970s generation satellites,

η_{solar} is about 11% at beginning of life and about 8% at end of life (10^{15} e^-/cm^2 irradiation), and J_{sc} is about 0.034 A/cm^2 at beginning of life and 0.029 A/cm^2 at EOL [reference 12, data on 1976 cells]. From figure 2, the peak of spectral response after 10^{15} e^-/cm^2 irradiation is about 0.5 A/W. Using these data, the expected efficiency at end of life under laser illumination is 2.4 times the solar efficiency, or about 19%, for wavelengths near the optimum (roughly 750 nm). This should be used only as a "ballpark" figure; an exact value will be dependent on the cell type and shielding.

This yields a power output equivalent to one sun of intensity at a laser power density (at orbit) of 570 W/m^2.

Ground System

The minimum spot radius of a transmitted laser beam is set by the diffraction limit,

$$r_{spot} = 0.61\, d\, \lambda / r_{lens} \tag{3}$$

where r_{lens} is the radius of the lens (typically a mirror) used to focus the beam, d the source to receiver distance, and λ the wavelength. The spot radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. As discussed below, the diffractive limit can only be achieved if adaptive optics are used to eliminate atmospheric beam spread. An optical system which achieves this spot diameter is referred to as "diffraction limited".

Using d=36,000 km (GEO), λ= 800 nm ($8 \cdot 10^{-7}$ m) and r_{lens}= 2.5 m, the spot radius is 7 meters. A 2.5 meter mirror is a large, but not record-breaking, telescope mirror. The illuminated area is 150 m^2. Increasing the mirror radius to 5 meters decreases the illuminated area to 38 m^2 at a considerable increase in mirror cost. For example, the cost of the 5 meter radius Keck telescope was $93M, compared to a cost on the order of $15M for a 2.5 meter radius telescope.

Pointing accuracy and atmospheric turbulence will degrade the effective spot size and hence increase the required laser power. In addition, for satellites which are not in geosynchronous orbit, it will be necessary to track the satellite with the laser. This can be a difficult operation for satellites in low earth orbit, due to the high slew rates involved.

Weather effects place another constraint on the operation of the system. Optimally, the laser ground stations should be placed on the peaks of mountains which are above most clouds, or on mostly cloud-free high plateaus which are surrounded by mountains [13]. To minimize the effect of unfavorable conditions at any one location, the lasers could be placed at widely separated locations. Use of four isolated laser sites will result in over 98.5% beam availability [13]; seven isolated locations will result in over 99.9% beam availability [14]. Since the eclipse power requirement is for 90 periods per year of roughly one hour, 99.9% beam availability corresponds to a 9% chance of losing illumination per year, or a 11 year mean time between loss of illumination. A typical contractual requirement for transponder availability allows for 53 minutes of transponder down time per year. Since the average eclipse duration is less than this, in general a single loss of illumination will not be a contractrual lapse if the satellite can be re-acquired quickly after eclipse and other failures do not occur.

Higher reliability could be achieved by either increasing the number of laser stations, or by mounting the laser stations on mobile platforms such as airplanes or ships.

ADAPTIVE OPTICS

Atmospheric turbulence limits the resolution of astronomical telescopes to about 4 microradians. At the distance of GEO this results in roughly 140 m spot diameter. Such a large beam spread is not acceptable for laser power levels likely to be available in the near-term.

Adaptive optical techniques must be used to reduce the beam divergence and jitter spread due to atmospheric turbulence. As a result of developments in astronomy and in defense laser applications, adaptive optics have been developed [15] which allow atmospheric turbulence to be removed to near diffraction-limited capability.

The adaptive optical component works by adjusting the surface of an optical element to exactly reverse the phase distortion of the downward sampled light; thus the sum of the phase distortion from the mirror and the atmosphere on the upward traveling laser light cancels to zero, and the beam is planar on leaving the atmosphere. This reverse distortion is done by means of a large number of individual mirror elements, each adjusted continuously by computer according to the sampling of the atmosphere.

Sampling the atmosphere requires light from the satellite to traverse the atmosphere along the laser path. The distortion in the beacon signal is then reversed to compensate the upward traveling power beam. This is possible because the time scale for atmospheric turbulence is much longer than the travel time for a light beam to traverse the atmosphere.

Ideally, the sampling light is a laser on board the satellite. The required beacon power is less than one watt. For an on-board laser, optimum atmospheric compensation requires that the laser be ahead of the receiving array by a distance equal to the travel time of the beam times the orbital velocity. For a satellite directly over the laser station,

$$\Delta = 2vd/c \qquad (3)$$

where Δ is the point-ahead separation distance, v is the orbital velocity, d is the altitude above the laser site, and c the speed of light. This assures that the returning power beam will be aimed at the spot where the receiving array will be after a round-trip travel time, and hence that the atmospheric path for the downward-directed beacon is the same as that of the upward-directed power beam. For GEO, this point-ahead distance is about 730 meters. If, instead of a beacon laser, light from the satellite itself is used, the atmospheric compensation will be degraded, since the downward atmospheric path sampled will be slightly different than the upward path taken by the power beam.

Since existing satellites do not have beacons, an alternate technique must be used. A light source at an altitude of ~90 km can be created by illuminating the sodium region in the ionosphere with a ground-based laser [16,17]; this signal can then be used to sample the atmosphere. The difference in altitude between the beacon and the spacecraft adds a slight source of error ("anisoplanatic error"); this error can be reduced somewhat by using more than one beacon.

The ability to compensate atmospheric turbulence rapidly degrades as the path length through the atmosphere increases, and it is likely that the maximum angle from zenith for which the system can be used will be in the range of 45° to 60°.

The effectiveness of the adaptive optic system is characterized by a Strehl ratio, which is the ratio of the actual peak intensity produced by the laser to the ratio which would be produced with no atmospheric distortion. For perfect compensation, the Strehl ratio would be unity. For systems of the type likely to be constructed in the near future, a Strehl ratio of 0.85 could be expected for a vertical beam, decreasing to 0.65 at 60° zenith angle.

For the 2.5-meter radius mirror discussed above, producing 570 W/m^2 would require a laser power output of 120 kW at a Strehl ratio of 0.85. Increasing the mirror radius to 5 meters (38 m^2 illuminated area) decreases the laser power required to 31 kW. This is a power level which is achievable with current technology.

LASERS

Lasers to be considered must operate in the wavelength range centered around the visible spectrum and near-infrared in which the atmosphere is nearly transparent. If specific molecular absorption peaks are avoided, the atmospheric has high transparency in the 500-850 nm wavelength range where the solar cell conversion efficiency is high.

Three laser types are well enough developed for consideration for near-term demonstrations of laser power beaming: the neodynium:YAG laser, the copper vapor laser or CV-pumped dye laser, and the RF free electron laser.

Pulse Response of Satellite Power System. Several of the laser types discussed have pulsed output. The pulse resonse of the solar cells, the array, and the power management and distribution system will significantly influence the ability of the satellite to make use of the beamed power. These issues are now under study [7,11]. For the lasers discussed below, only the copper vapor (CV) laser has a pulse format with pulses that are likely to adversely affect the solar cell and array performance. YAG lasers can produce continuous (CW) illumination, and the GHz micropulse frequency of the RF FEL is fast enough that the cell response is essentially to continuous illumination, although the macropulse format may influence the output if the output duty factor is low. If the CV laser is chosen, the pulse response of the solar cells and power system of satellites under consideration will have to be measured and, if necessary, the laser pulse format modified to minimize adverse effects.

YAG Lasers. Of currently developed laser technologies, the highest power CW lasers in the wavelength range of interest are Neodymium doped Yttrium-Aluminum Garnet (Nd:YAG). The wavelength of 1064 nm is theoretically possible to convert by silicon cells, but in practice, the production-technology silicon solar cells used on satellites currently flying have very low performance at 1064 nm. Further, the long wavelength response degrades rapidly in a radiation environment, and thus very little response at 1064 nm would be expected at satellite end of life. Frequency doubling the YAG to 530 nm results in a considerably better performance; however, frequency doubling will reduce both the laser efficiency and the laser power.

The best KD*P frequency doublers have an efficiency of 75 to 80% in pulsed operation. Commercially available frequency doublers typically are only 50% efficient. Since frequency doublers are nonlinear, the efficiency increases with the pulse intensity. Continuous-wave frequency doublers are considerably less efficient, typically in the range of 10%, since the required high powers needed for efficient operation cannot be maintained at CW operation due to thermal distortion of the crystal.

At 532 nm the spectral response of the radiation-damage cell has decreased from the peak value to roughly 0.38 A/W, requiring the laser power to be increased by 30% to achieve the same power.

YAG lasers are currently available with average power up to 2.4 kW [18], at a cost of about $175/watt, and higher power lasers are under development. Such high average power lasers are available in both pulsed and CW operation, but typically have output quality of 40-50 times diffraction-limited performance [19]. High efficiency diode-pumped YAG lasers with average power over 1 kW and near diffraction-limited performance are beginning to be available, and 2-3 kW lasers are currently under development [19].

For the power levels required for missions of interest, many such lasers would have to be operated together. A simple technique to do this is to operate the lasers in pulsed mode, and interleave the pulses from each laser into a single output. For CW lasers, coherent addition could be done by operating the individual lasers as amplifiers of a single master oscillator, to produce diffraction-limited performance.

Including the decreased spectral response at 532 nm, full power on the satellite as calculated would require 156 kW of laser power using a 2.5 m mirror radius. At 80% doubling efficiency, this could be done with 98 2-kW lasers, at a cost of around 34 million dollars (not including the cost of frequency doublers and interleaving optics.) The 5-meter radius mirror (39 kW output) would require 25 2-kW lasers, at a cost on the order of 9 million dollars.

Copper Vapor Lasers. Copper vapor lasers are inherently pulsed lasers, but have been demonstrated to produce average powers at levels of interest. The highest average-power continuously-run laser facility in the world is the AVLIS (Atomic Vapor Laser Isotope Separation) system running at Lawrence Livermore National Laboratories. This laser uses a twelve chains of copper-vapor lasers to pump dye lasers, and has demonstrated extremely high reliability and continuous operation. The copper vapor lasers produce roughly 10 kW of average power at the two copper lines, 511 and 578 nm, with a beam quality of rougly fifteen times diffraction limited. An upgrade currently in progress will improve this to 15 kW average power at 5 times diffraction limited beam quality. The output is a 40 nS pulse with a repetition frequency of up to 26 kHz.

This laser is used to pump a dye laser, at about 35% efficiency, to obtain nearly diffraction-limited beam quality. About 5 kW of diffraction-limited laser power is available in the near term. In principle, operation at any wavelength of choice could be obtained by choice of an appropriate dye to be pumped by the copper laser. From the calculations above, this power output could produce 4% of full satellite power at GEO using a 2.5 m mirror with adaptive optics, and could produce 16% of full satellite power using a 5 meter mirror.

This laser output has been directed to a telescope output for vertical beaming. In this demonstration, the pulse from a copper vapor / dye laser output at 589 nm was stretched and then directed through a 1 meter telescope for fluorescence of the sodium layer of the ionosphere. An operational version of this system is scheduled to be shipped to the 10-meter diameter Keck telescope in Hawaii in early 1995 for use as an adaptive optics system.

Free Electron Lasers. For a more advanced system, the free-electron laser (FEL) is a very attractive choice. A FEL has potentially very high efficiency as well as high power and is, in principle, tunable over a wide range of wavelengths, down to as low as <200 nm. A disadvantage is that high continuous power systems are not yet demonstrated at the wavelengths of interest. Free electron lasers have been proposed in the multi-megawatt power range.

Free-electron lasers can be based either on induction or RF linear accelerators. The induction laser is potentially capable of high power, but is less well developed, and has not yet been operated in the wavelengths required. It may be a candidate for future, high-power missions. RF lasers are currently under development at power levels of interest, and are likely to be operational in the near future.

The APLE laser now being built at Boeing is a megawatt class RF FEL to operate at a wavelength of 10 microns (tunable to ±10%). The initial power level will be 100 kW average power, with a 25% duty factor. This is to be built at the Boeing facility in Seattle, but is designed to be sent to the HELSTAT laser facility at White Sands Missile Range for operation. This laser is designed to allow adaptation to operation at lower wavelengths. FEL operation at wavelengths as low as 500 nm has been demonstrated at Boeing, but not at the high power level required.

Another RF FEL facility is the Rocketdyne "Compact Operational Laser" (COL). This laser, not yet operational, is intended to have a 1 kW average power at 1060 nm. The power level is upgradable to ≥10 kW by upgrading the accelerator klystrons [20]. Decreasing the wavelength to 800 nm is quoted as "not difficult." The output of this laser is a string of RF micropulses, with each string of pulses lasting 3.5 microseconds and repeated at 360 Hz.

Conclusions

Illumination of a satellite in geosynchronous Earth orbit at levels sufficient to provide full spacecraft power should be feasible with arrays of lasers using technology likely to be available in the near-term. The primary limitation at the moment is beam spread due to atmospheric distortions; this could be reduced by the use of adaptive optics to compensate for atmospheric turbulance.

The commercial satellite industry should be able to reap significant economic benefits through the use of power beaming. The inclined-orbit mode has eliminated fuel as the life limiting factor for synchronous orbit communications satellites. Now battery lifetime is the limiting factor. Power beaming can provide supplemental power for satellites with failing arrays, or primary power in the case of failed batteries. Today there are more than 22 satellites operating in extended life mode, generating total revenues potentially approaching $500M. This is a large incentive for laser power beaming.

In the future, satellites may be designed without large batteries, allowing an increase in payload on the order of 50%, for considerable additional savings.

Acknowledgements

We would like to thank Andrew Meulenberg of Comsat Research Laboratory for his enthusiastic promotion of the concepts discussed here and for many helpful discussions, Herb Friedman of Lawrence Livermore National Laboratories for background information on laser technology and information on the AVLIS lasers, Robert Lamb at Boeing for information on the APLE laser, and John D.G. Rather for initiating the SELENE project.

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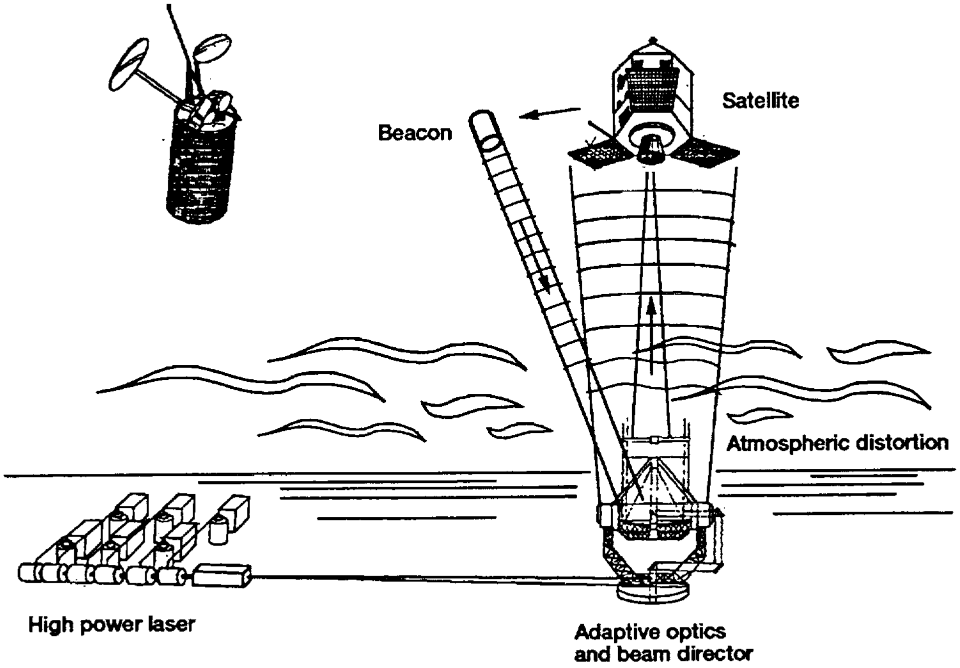

Figure 1.—Laser power beaming to satellites in geosynchronous orbit.

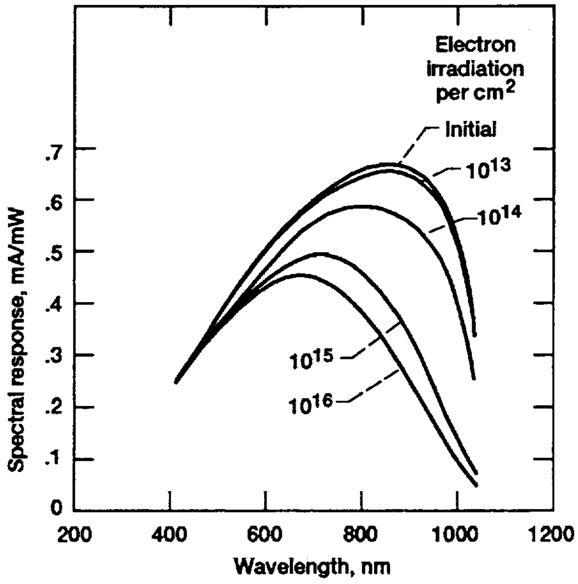

Figure 2.—Spectral response (amps/watt) of a 10 Ω-cm silicon solar cell as a function of wavelength, for various 1-MeV electron irradiation levels [from ref. 10, 1974]. 10^{15} e$^-$/cm^2 corresponds to roughly 30 years in geosynchronous orbit (depending on shielding).

Appendix 1.

"Satellite Eclipse Power by Laser Illumination"

paper IAF-90-053

reprinted from
Acta Astronautics, Vol. 25, No. 4, pp. 229-233 (1991)

Acta Astronautica Vol. 25, No. 4, pp. 229–233, 1991
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0094-5765/91 $3.00 + 0.00

SATELLITE ECLIPSE POWER BY LASER ILLUMINATION

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(Received 5 September 1990)

Abstract—A method is proposed to eliminate the energy storage system required to power a satellite in geosynchronous orbit during eclipse. An array of high-power CW lasers is situated at one or more ground locations in line of sight of the satellite, preferably on mountaintops. The lasers are provided with a tracking system, and lenses or mirrors of sufficient size to reduce the beam spread due to diffraction. As the satellite enters eclipse, the laser arrays illuminate the solar arrays on the satellite to a level sufficient to provide operating power.

1. INTRODUCTION

Geosynchronous Earth orbit (GEO) satellites are a valuable portion of commercial space activities. All satellites now operating in GEO are powered by solar arrays. For operation during eclipse periods, when the Earth shadows the satellite from the sun, a battery back-up system charged by the solar array provides power.

The geosynchronous orbit is in eclipse for only a short period of time around the equinoxes, typically about 90 days total per year. Eclipse duration is maximum at the equinox, when it reaches just under 70 min, or about 5% of the orbit.

On a typical communications satellite, about one-fifth of the total satellite mass is the power system [1]. For a 5 kW power system, the power system total mass is roughly 900 kg. [2]. The energy storage system, for current nickel-hydrogen batteries used in GEO, comprises 42% of the power system weight. An additional 37% of the power system mass is electrical power conditioning, a significant portion of which is needed for battery charge regulation. Only 21% of the power system is actually the solar array, and about 10% of the array area is dedicated to recharging the batteries. It is remarkable that over half of the mass of the power system has no other function than to provide power for $<1\%$ of the operating time. Eliminating the requirement for an energy storage system could reduce satellite mass by 10%.

In this paper a method of eliminating the storage system is discussed, where the satellite is illuminated during eclipse by a ground-based laser.

The proposed system is simple. An array of high power continuous-wave (CW) lasers is situated at one or more ground locations in line of sight of the satellite, preferably on mountaintops. The lasers are provided with a tracking system, and lenses (or mirrors) of sufficient size to reduce the beam spread due to diffraction. As the satellite enters eclipse, the laser arrays illuminate the solar panels on the satellite to a level sufficient to provide operating power.

No added elements are needed for the satellite. The solar array needed to receive the beamed power is already in place on the satellite. Laser power is required only for periods of <70 min per day for 90 days out of the year. This allows ample time for laser refurbishment and preventative maintenance. The fact that the laser is on the Earth allows considerable design simplification; unlike in-space systems, where any failure is fatal, terrestrial systems can be easily repaired, so highly redundant systems are not required. Since one of the failure modes of a satellite is battery failure, by eliminating the battery the mean time to failure, and hence the expected life, of the satellite can be increased.

Each ground laser station can successively illuminate several satellites at different longitudes (see Fig. 1). As one satellite exits the eclipse region, the laser is retargetted to another satellite entering the eclipse. If the laser could scan angles down to the horizon, ten satellites could be successively illuminated. Even if a ground-based laser can scan only an angle of $\pm 45°$ from the zenith, a single laser station could provide power for five satellites at different longitudes.

Solar cells in GEO are subject to degradation in power due to trapped radiation and solar flares. Solar arrays are typically oversized in order to provide power under worst-case end of life conditions. Once set up to provide eclipse power, the laser power system described could also be used to provide supplementary power if needed to compensate for radiation damage to the arrays.

With some exceptions [3–6] most discussions of power transmission in space focus on microwave transmission. Laser transmission was chosen over microwave for several reasons. First, optical wavelengths are considerably shorter than microwave wavelengths, which reduces diffraction and so allows a much narrower beam. Consequently, the receiver and the transmitter (i.e. the photovoltaic cells and the laser) can be considerably smaller for laser transmission. Secondly, if the laser wavelength is selected

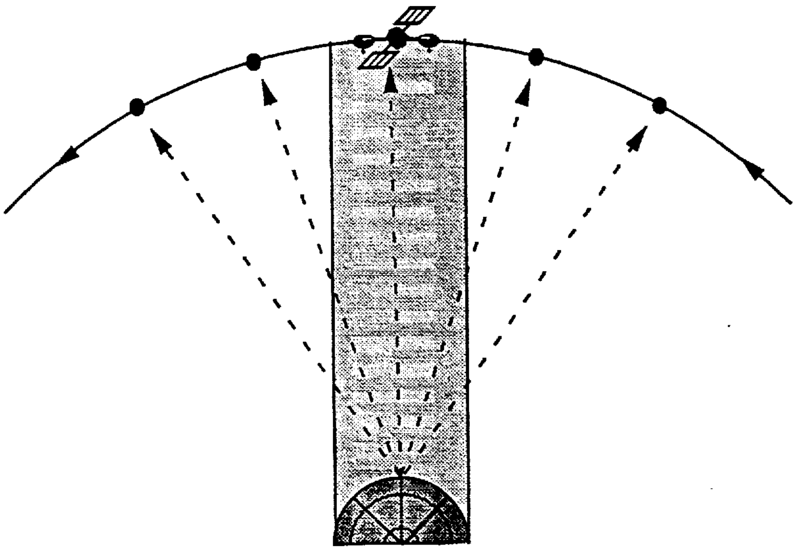

Fig. 1. A single ground station can illuminate several satellites in GEO in sucession as each one enters the Earth's shadow.

properly, the receiver can be the same solar array used to provide normal power. An additional microwave rectenna is not required on the satellite.

2. PHOTOVOLTAIC RECEIVER

The best photovoltaic cells can be expected to convert about 50% of monochromatic incident light at the optimum wavelength into electricity. The efficiency drops to zero for wavelengths much longer than the optimum. For wavelengths shorter than the optimum, the conversion efficiency for monochromatic light η_{laser} is approximately:

$$\eta_{\text{laser}} \approx \eta_{(\text{optimum})}(\lambda_{\text{laser}}/\lambda_{\text{cutoff}}) \qquad (1)$$

λ_{cutoff} is theoretically determined by the bandgap of the solar cell material:

$$\lambda_{\text{cutoff}} = 1240/E_g \qquad (2)$$

for λ_{cutoff} in nanometers (nm), where E_g is the bandgap of the semiconductor material in electron volts. In the real world, solar cells do not perform optimally for photon energy out to the bandgap, since light near the bandgap is only weakly absorbed. For example, single crystal silicon has a bandgap wavelength of about 1100 nm; however, the peak of the spectral response is typically near 950 nm for the solar cells used on existing spacecraft. The efficiency drops rapidly toward zero at longer wavelengths. At 1060 nm, a wavelength of interest for lasers, the efficiency is down by a factor of three or more from the peak. Figure 2 shows a measured spectral response of a conventional silicon solar cell of the type similar to those used for spacecraft applications [7]. The response is quite linear out to about 950 nm, but drops off rapidly above this value. However, it is possible to design solar cells to increase the long-wavelength performance, using techniques such as light-trapping [8].

For cells near the optimum bandgap for solar conversion, such as GaAs, the monochromatic light efficiency η (optimum) can be roughly estimated as double the conversion efficiency for sunlight. The best GaAs solar cells are slightly under 24% efficient for the solar spectrum, and thus can be expected to be about 50% efficient at the optimum wavelength.

The minimum spot radius of a transmitted laser beam is set by the diffraction limit,

$$r_{\text{spot}} = 0.61\, d\lambda/r_{\text{lens}} \qquad (3)$$

where r_{lens} is the radius of the lens or reflector used to focus the beam, d the source to receiver distance, and λ the wavelength. The spot radius is here defined as the first zero in the diffraction pattern; this contains 84% of the beam energy. As discussed below, the diffractive limit can only be achieved if adaptive optics are used to eliminate atmospheric beam spread.

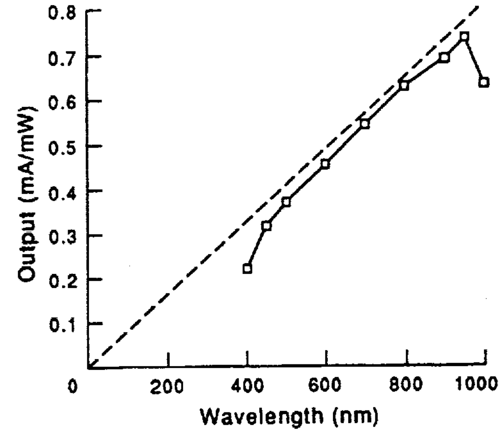

Fig. 2. Measured output of a standard silicon solar cell as a function of incident wavelength. The dashed line indicates the ideal (unity quantum efficiency) spectral response.

If the spot size is smaller than the receiving array, the laser wavelength is preferably chosen at the optimum value for the solar cell performance. However, if the diffraction-limited spot size is larger than the receiving array, it is desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency. Since efficiency only decreases proportionately to λ, while the illuminated area is proportional to the spot radius squared (if atmospheric beam spread is eliminated), it is desirable to use the shortest practical wavelength. The opacity of the atmosphere to short-wavelength ultraviolet places a lower limit to the wavelength at about 350 nm.

3. OPTICS

A key element in achieving small spot sizes is the use of a large optical aperture on the ground system. For optimal systems, the lens size should be in the scale of meters. While it may be argued that meter-scale optics are expensive (e.g. the Hubble Space Telescope is a 2.4 m dia mirror), it must be kept in mind that the optics do not have to be of telescope quality, and need only operate at a single wavelength. The optics may be fresnel lenses or holographic optical elements, which may be very cheaply manufactured. Other programs, such as the U.S. SDIO research effort, have concluded that manufacturing 4–8 m mirror elements will not be a major difficulty.

In the real world, pointing accuracy and atmospheric turbulence degrade the effective spot size. Achievable pointing accuracy is high enough that this is not a limiting factor. Atmospheric turbulence limits the resolution limit of astronomical telescopes to slightly < 1 arc sec, or about $4\,\mu$rad, increasing slightly at shorter wavelengths. At the distance of GEO, 3.5×10^7 m, this contributes about 135 m to the spot diameter.

The effect of turbulence is greatly reduced by operating the laser from the highest possible altitude, such as a mountain peak, to decrease the optical path through the atmosphere. An alternate possibility is to operate the lasers from airborne locations such as high-altitude aircraft or balloons. Since the lasers need only be operated for periods of roughly an hour, this may be feasible, although the laser power source and the increased difficulty of pointing stability could provide significant constraints.

Better performance can be achieved by using techniques which compensate for atmospheric distortion [9]. One such technique is the flexible mirror telescope, where the mirror pointing and shape is continuously adjusted to compensate for distortions in the shape of the wavefront due to turbulence. The 1.2 m telescopes at the U.S. Air Force Maui Optical Station, located on Mt Haleakala at 3 km altitude, resolve objects in orbit to a resolution of $0.4\,\mu$rad [10]. This resolution would contribute about 13 m to the spot diameter in GEO. An alternate technique is to use an active phased array, or phase conjugate mirror. In this case a pilot beam would be beamed downward from the spacecraft to the phase conjugation system, which would synthesize a beam precisely opposite in phase and direction to the pilot beam. This would then be retrodirected to the satellite with the atmospheric distortion corrected.

Weather effects place another constraint on the operation of the system. Optimally, the laser ground stations should be placed on the peaks of mountains which are above most clouds. To minimize the effect of unfavorable conditions at any one location, the lasers could be placed at widely separated locations. Use of seven isolated locations will result in over 99.9% beam availability [9].

4. LASERS

Lasers to be considered must operate in the wavelength range centered around the visible spectrum in which the atmosphere is nearly transparent. The minimum wavelength is about 350 nm, limited by atmospheric absorption by ozone [9]. The maximum wavelength to be considered is 1100 nm, unless new photovoltaic receivers responsive to long wavelength light are to be developed.

The highest power lasers currently available use carbon dioxide (CO_2) as the lasing medium. While CW power levels of over a megawatt have been demonstrated, the wavelength of 10600 nm is far too long to be considered. If future satellites use a thermal, rather than photovoltaic, energy conversion system, however, use of CO_2 lasers may be an option.

Of currently developed laser technologies, the best high-power CW lasers are Neodymium doped Yttrium–Aluminum Garnet (Nd : YAG). The wavelength of 1064 nm is theoretically near the optimum energy for conversion by a silicon solar cell, however, in practice, solar cells are optimized for shorter wavelengths and do not have very high efficiency at 1064 nm. Further, the long wavelength response degrades rapidly in a radiation environment, and thus Nd : YAG illumination would result in decreasing power at the satellite end of life. Frequency doubling the Nd : YAG to 530 nm results in a considerably better wavelength, however, frequency doubling will reduce both the laser efficiency and the laser power by roughly a factor of two.

The best currently available Nd : YAG lasers have averaged CW power of 1 kW [11].

Argon ion lasers, with primary emission lines at 514 and 488 nm, are also at a good wavelength, but have extremely low electrical to light conversion efficiencies.

An alternative currently being developed is the solid state diode laser. The highest power GaAs diode lasers operate at about 795–820 nm, which is nearly optimal for existing silicon solar cells. Shorter wavelength GaAlAs lasers can be manufactured, which would be preferred for GaAs solar cells. An array consisting of a very large number of individual lasers could yield the required power. Monolithic arrays of diode lasers have recently demonstrated power densities as high as 80 W/cm^2 and CW power levels of 1 kW [12]. The problem of beam-combination from a large number of individual diode beams is a technological problem which still must be solved. The current cost of commerical high-power diode laser arrays [13] is about $400 per output watt, however, it is expected that the price will decrease as the production increases. Costs as low as $1/W have been suggested as achievable with future diode laser arrays, assuming high volume production.

Excimer lasers are available with very short wavelengths. 750 W Xenon Chloride (XeCl) excimers lasers have been manufactured by Lambda Physik [14], with a laser wavelength in the u.v. at about 308 nm. Another alternative, XeF, lases at 351 nm. Other excimer laser gasses are typically below the wavelength range of atmospheric transparency, although it is important to note that a 1-MW KrF laser design is discussed by De Young *et al.* [4] and others [15] operating at 248 nm.

For a more advanced system, the free-electron laser (FEL) is a very attractive choice. An FEL has potentially very high efficiency as well as high power [16] and is, in principle, tunable over a wide range of wavelengths, down to as low as <200 nm. FELs have been proposed in the multi-megawatt FEL to be built at White Sands for defense research. Existing FELs built for defense research are commonly quoted as operating in the "multi-kilowatt" power range. A FEL operating at wavelengths as low as 600 nm has recently been demonstrated [17]. A disadvantage is that the systems are likely to be heavy, and are not yet demonstrated at the wavelengths of interest.

Finally, the energy efficiency of the laser is an issue, although not the major criterion for selection. While many lasers have low conversion efficiency, power is extremely cheap on Earth compared to the cost of power in space. High efficiency is the primary feature of semiconductor diode lasers. Existing high-power lasers have relatively low efficiency, since the conversion from electrical power to laser power typically requires an intermediate step, e.g. a flashlamp. The best flashlamp-pumped Nd : YAG lasers [11] have an efficiency (electrical input to laser output) of about 6%. Diode-pumped Nd : YAG lasers have roughly double this efficiency. The power efficiency of excimer lasers is typically about 10%, e.g. for existing Kr–F excimer laser. Lasers being developed have considerably higher efficiency. Available high power diode laser arrays [13] have a total energy efficiency of 40%; a 70% efficiency has been obtained in the laboratory [4, 6]. Efficiencies as high as 84% are possible. Free electron lasers also have quite high efficiencies, with efficiency expected to be as high as 65% [15].

Alternative discussions of lasers for space power transmission applications, focused on space-based systems using advanced technology lasers and PV receivers, can be found in studies by NASA Langley Research Center, cited in Refs [4–6].

5. BASELINE SYSTEM

Consider a baseline system with a wavelength λ near 1 μm, or 1000 nm (1×10^{-6} m). This is the wavelength range for a Nd : YAG laser, and close to that of a GaAs laser diode array. It is slightly longer than the optimum conversion wavelength for a Si solar cell. The distance d (surface-GEO) is 3.5×10^7 cm, and the lens diameter is 2 m. For diffraction limited beam spread, the diffraction-limited spot radius at GEO is 23 m. This is sufficiently small that the beam spread at the array is almost entirely due to atmospheric turbulence. The turbulance-limited spot size is about 15,000 m^2.

For 10 kW of baseline power with a solar array efficiency of 18.5%, the array area is 40 m^2, and so the array intercepts only about 0.25% of the beamed power. The required beam power would be 8.5 MW.

It is reasonable to expect that use of adaptive optics could reduce the atmospheric beam spread by a factor of ten. The spot size is now limited by diffraction. If the laser wavelength is then reduced by a factor of two to ~500 nm, the total spot radius at GEO is 13 m. The illuminated area is 560 m^2, and the array now intercepts 7% of the incident power. The net result is that the laser power needed is ~500 kW.

The required 500 kW could be provided, for example, by twenty-five 20-kW laser units, to allow any single unit to be taken off line without system failure. Such power levels are high compared to those achieved by current technology CW visible light lasers, but in the range likely to be reasonably achievable for future high-power lasers. It is many orders of magnitude higher power than currently achieved by diode lasers. Problems of tracking and reliability remain to be addressed.

6. CONCLUSIONS

Illumination of a satellite in geosynchronous Earth orbit at levels sufficient to provide full spacecraft power should be feasible with arrays of lasers using technology likely to be available in the near-term. The primary limitation at the moment is beam spread due to atmospheric distortions; this could be reduced by the use of adaptive optics to compensate for atmospheric turbulance.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
August 1992

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Laser Beamed Power: Satellite Demonstration Applications

5. FUNDING NUMBERS
WU-506-41-11
C-NAS3-25266

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Sverdrup Technology, Inc.
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2001 Aerospace Parkway
Brook Park, Ohio 44142

8. PERFORMING ORGANIZATION REPORT NUMBER
E-7629

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR-190793
IAF-92-0600

11. SUPPLEMENTARY NOTES
Prepared for the 43rd Congress of the International Astronautical Federation sponsored by the International Astronautical Federation, Washington, D.C., August 28–September 3, 1992. Project Manager, Dennis J. Flood, Power Technology Division, (216) 433-2303.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

It is possible to use a ground-based laser to beam light to the solar arrays of orbiting satellites, to a level sufficient to provide all or some of the operating power required. Near-term applications of this technology to providing supplemental power for existing satellites are discussed. Two missions with significant commercial pay-off are supplementing solar power for radiation-degraded arrays, and providing satellite power during eclipse for satellites with failed batteries.

14. SUBJECT TERMS
Lasers; Satellites; Photovoltaics

15. NUMBER OF PAGES
19

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102