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Near-term feasibility demonstration of laser power beaming

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ABSTRACT

A mission to recharge batteries of satellites in geostationary orbits (geosats) may be a commercially viable application which could be achieved with laser systems somewhat larger than present state-of-the-art. The lifetime of batteries on geosats is limited by repetitive discharge cycles which occur when the satellites are eclipsed by the earth during the spring and fall equinoxes. By coupling high power lasers with modern, large aperture telescopes and laser guide star adaptive optics systems, present day communications satellites could be targeted. It is important that a near term demonstration of laser power beaming be accomplished using lasers in the kilowatt range so that issues associated with high average power be addressed. The Laser Guide Star Facility at LLNL has all the necessary subsystems needed for such a near term demonstration, including high power lasers for both the power beam and guide star, beam directors and satellite tracking system.

1. GEOSTATIONARY COMMUNICATIONS SATELLITES

Although geosats do receive solar flux 24 hours a day under most circumstances, there are two periods during which eclipses occur, the spring and fall equinox. The eclipse periods last for about 30 days each with maximum darkness lasting about 72 minute. Although these two periods account for only a small portion of the total yearly illumination, over a period of approximately ten years, the storage batteries lose their ability to retain a charge and the end of their useful life is approached.

A power beaming laser system must supply a fraction of an equivalent solar flux during the eclipse period with high reliability and availability. An equivalent solar flux is that flux of monochromatic light which produces the same electrical output as the broad band solar flux. The fraction is determined by the solar cell characteristics and a trade study between battery lifetime, charging rate, laser capital and operating costs. The optimum wavelength, pulse format, and average power of the laser is determined primarily by the solar cell characteristics and the results of the trade study. The technical requirements for the laser and beam director system will be enumerated below but the economic trade studies remain to be done. These studies await an accurate assessment of laser costs, satellite battery system information, and economic studies of geosat operations.

An understanding of the orbital dynamics of geosats is needed to determine how many lasers are needed to access all the satellites in geostationary orbit for the battery charging application. Figure 1 illustrates the situation viewing the earth's equatorial plane at either of the equinoxes. In this drawing, the earth's polar axis is perpendicular to the plane of the figure and the ecliptic plane (the plane of the earth's rotation about the sun) is at the 23.5 degree inclination.

Figure 1. Satellites in geostationary orbit at the equinox.

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The figure shows the earth with radius, R_e , equal to 6,337 km and the geostationary orbit with radius, R_{geo} , equal to 42,164 km. Light from the sun at a distance of 1 Astronomical Unit (AU), or 1.496×10^8 km, can be considered parallel and casts a shadow approximately $2R_e$ wide. At the equinox, the geostationary orbit intercepts the maximum amount of the earth's shadow and represents 17.4 degrees of the orbit. The transit time of a single geosat is $(17.3/360) \times 24$ hours or about 70 minutes.

Figure 2 shows a flat projection of the earth with longitudinal lines spaced at 30 degrees. At the bottom of the figure is a compilation¹ of all the communication geosats in orbit as of 1991. Within the 90 degrees of longitudinal spanned by the North American continent, there are approximately 44 geosats corresponding to a spacing of about 2 degrees. Thus, at any given time during a night near the equinox, there are 8-9 geosats in the earth's shadow. If the laser can illuminate only one geosat at a time, only about 5-6 of the 44 satellites over the North American continent can be serviced during the nighttime period.

Figure 2. Number of geostationary communications satellites.¹

There are several concepts which could permit one installation to access more than one geosat at a time. The Large Binocular Telescope, to be built in Arizona, will house two telescopes on a common mount. This arrangement could double the number of accessible satellites (at double the laser power) with many shared facility costs. Another concept would use a large spherical primary mirror with multiple beams at different angles to address each satellite in the shadow. There would be large aberrations in such a scheme but they could be compensated by fixed corrector plates or as part of the adaptive optics system.

2. LASER POWER REQUIREMENTS

In the absence of turbulence in the atmosphere, the specific laser power delivered to a satellite from earth depends upon the orbital radius, aperture of the beam director, laser wavelength, and degree of coherence of the laser light. This relationship is described as follows:

$$I_L = P_L \eta_a / (\lambda R / D)^2 \quad (1)$$

where:

- P_L = total laser power at the aperture of the beam director
- η_a = atmospheric transmission
- λ = laser wavelength
- R = satellite orbit radius
- D = aperture diameter

For most satellite applications, the size of the laser beam at orbit will be much larger than a reasonable solar cell array size. In these cases, the laser beam overfills the array and only the laser power density, I_L , given by Eq. 1 is important.

For a geosat at an orbital distance 37 Mm (megameters) and the solar constant of 1.37 kW/cm^2 , Eq. 1 predicts a power level of 600 kW for a wavelength of 850 nm, an atmospheric transmission of 0.85, and a beam director aperture of 3 m. The choice of wavelength coincides with the spectral peak of present day solar cells, as will be shown below, and the beam director aperture is typical of the new generation of devices developed for the Air Force. It will be shown below that several factors can lower this power level by factors of 2-3, but it is important to note that such a power level is far below the value required by most SDIO missions for which significant research and development has been expended. On the other hand, this power level is almost two orders of magnitude higher than the highest power visible laser system, at least in terms of a system which could operate for long periods of time and with high reliability and availability as would be required by a power beaming system.

3. LASER WAVELENGTH

The optimum laser wavelength is determined primarily by the peak wavelength for solar cell conversion. The conversion efficiency of several popular solar cell materials is shown in Fig. 3.2. Although the materials denoted by curves 5 and 6 might be attractive in terms of an eye safe laser wavelength and less distortion by the atmosphere, these materials are not efficient converters of natural sunlight and have not been fabricated into solar cells at the present time. The most widely used material is silicon which has a peak conversion efficiency of about 40% at a wavelength of about 900 nm. The material with the peak conversion efficiency is Gallium Arsenide at about 60% at a wavelength of about 850 nm.

These curves are plotted for undamaged material. Radiation damage has two effects upon the solar cells. First, the conversion efficiency is lowered and second, the long wavelength cutoff is reduced. The loss of conversion efficiency reduces the battery charge even before the geosat enters the eclipse periods. This causes the batteries to discharge to a deeper level and shortens the battery lifetime more rapidly as it nears its end of life. Second, reducing the long wavelength cutoff defines the longest laser wavelength allowable for a power beaming system. The data indicates that for operation at the popular solid state laser wavelength of 1.06 microns, a ten year old, radiation damaged silicon solar cell is only 20% as efficient as compared to operation at 0.9 micron for an undamaged cell. Also, the optimum wavelength shifts from about 0.920 microns to 0.750 micron as the cell fully ages. A reasonable choice for optimum laser wavelength averaged over its lifetime is 0.850 micron.

Figure 3. Conversion efficiency of several solar cell materials as a function of illumination wavelength.

An important benefit of monochromatic irradiation of solar cells is that the conversion efficiency can be substantially higher than is possible for broad band solar radiation. These high efficiencies have been measured in solar cells as shown in Fig. 3. Since the normal range of conversion efficiency for broad band solar irradiation is in the 10-20% range, there is a factor of about 2-3 to be gained using monochromatic light.

INTENSITY = 500 mW/cm² TEMPERATURE = 25°C

Figure 4. Theoretical conversion efficiency of photovoltaic cells for monochromatic light.

4. LASER PULSE FORMAT

Since present solar cells have been optimized for continuous light, the optimum laser pulse format is CW. High power visible lasers have not been developed with CW format for a variety of reasons, primarily because of unfavorable kinetics and heat transfer mechanisms. A study was recently completed⁴ to determine the effect of the laser pulse format on the conversion efficiency of solar cells. Although the primary goal of the study was to determine the relative merits of two specific lasers, namely Induction-Free Electron Lasers (I-FEL) and Radio Frequency-Free Electron Lasers (RF-FEL), the results can be extended to provide insight to other lasers as well.

I-FELs have low duty cycles, of the order of 5×10^{-4} , so that the ratio of peak to average power is about 2000. RF-FELs have somewhat higher duty cycles, but since their pulses are much shorter than the solar cell response time of about a nanosecond, the effective duty cycle can be of the order of 10^{-1} . A common characteristic of present solar cells is the presence of a rather large internal resistance. At the high peak power levels, a significant voltage is dropped across this internal resistance, thereby lowering the conversion efficiency of the solar cell. Thus, laser pulse formats with high duty cycles are more efficient. The results of the study represent the first attempt at a systematic study of the effects of peak power on conversion efficiency and are not very complete. However, the trend is clear and points to a duty cycle greater than a percent for high conversion efficiency. For pulse formats with greater peak power enhancement, the design of solar cell arrays must be changed to reduce the internal resistance.

5. ADAPTIVE OPTICS SYSTEMS

Up to this point, the effect of atmospheric turbulence on the propagation of laser beams to satellite orbits has been neglected. The general effect of turbulence is to increase the divergence of the laser beam to that which would be obtained had the beam director aperture been reduced to the coherence scale of the atmosphere. The coherence scale is a function of the atmosphere along the beam path and of laser wavelength. At 850 nm, typical values range from less than 10 cm at poor sites, to 20 cm at selected sites, to 30 cm at the best astronomical sites in the world. These values of the coherence scale are not the largest values observed but represent the median over long times as would be appropriate for power beaming.

The effect of the coherence scale on the complexity of an adaptive optics systems occurs in several ways. The number of independent channels scales as the ratio $(D/r_0)^2$ and the bandwidth of the control loop scales approximately as (V_w/r_0) where D is the aperture diameter and V_w is the wind velocity. Hence, for a large telescope at a moderate site, the number of control channels can be several thousand and the bandwidth of the control system can be several hundred Hertz. Furthermore, the wave front sampling frequency is about ten times the bandwidth so that the wave front sample rate can easily be of the order of a kilohertz. The power of a beacon laser also scales as the inverse cube of the coherence scale. Thus, moving to a better site can significantly reduce the complexity of an adaptive optics system, but this benefit must be balanced by the logistics of construction and operation at the top of a mountain.

The adaptive optics system senses the wave front distortion from a beacon in the satellite path and controls a deformable mirror in the optical train of the power beaming laser to restore the wave front to a flat condition. For satellites, there is a lead-lag problem resulting from the finite transit time of the laser beam to the satellite and a simple glint from the satellite itself cannot be used as the beacon. A boom could be flown out ahead of the satellite corresponding to the lead distance but this is a cumbersome situation and would not apply to satellites already in orbit. The preferred method is to create an artificial beacon at the appropriate lead angle using laser scattering off sodium atoms^{5,6} in the mesosphere at 100 km. Our group at LLNL⁷ has generated the brightest sodium-layer laser guide star using a powerful laser developed for isotope separation.

The laser power needed to generate a suitable beacon for a large telescope at a moderate site is several hundred watts and laser powers of this magnitude which are tunable to the sodium resonance line at 589 nm are routinely produced by the Laser Isotope Separation Program. Figure 5 shows a 1100 watt laser beam propagated upwards from the LLNL site and Figure 6 shows the sodium-layer laser guide star taken at a distance of four miles from the site, hence, the elongation of the guide star as the beam passes through the 10 km thickness of the mesospheric sodium layer. When viewed from directly below, the guide star appears as a round spot which is optimum.

The laser system which generated the beam shown in Fig. 5 was developed by the Laser Isotope Separation Program and consists of a series of copper vapor lasers which pump several chains of dye lasers, see Fig. 7. For the beacon laser, the highest power dye laser chain is retuned to the sodium wavelength at 589 nm and frequency modulated to match the spectral profile of the mesospheric sodium. The average power output of the copper and dye laser systems is 10 kW and 3 kW, respectively. In addition to the high power chain which is used for the sodium beacon, there is another kilowatt remaining which could be retuned to 850 nm and used for a power beaming demonstration in the near term using the LLNL site.

The control system which corrects for atmospheric turbulence, either for incoming starlight in the astronomy application, or outgoing laser radiation for the power beaming application, is shown in Fig. 8. The laser beam is propagated out of a separate beam director located a short distance from the main telescope (or beam director). A pinhole in the optical path of the telescope blocks the Rayleigh scattered beam and allows the sodium spot to pass onto the wave front detector.

Figure 5. Propagation of the LLNL 1100 watt laser beam tuned to the sodium wavelength.

Figure 6. Sodium-layer laser guide star photographed at a distance of four miles from the propagation site.

Figure 7. AVLIS laser system design concept.

Figure 8. Detailed design of the LLNL laser guide star optical system.

Both the laser and the light from the beacon reflect off a tip-tilt and deformable mirror and onto a dichroic mirror. The beacon light is passed into a wave front sensor and information is fed into the wave front reconstruction computer which drives the deformable mirror closing the main control loop. Information for the tip-tilt sensor is derived from a glint off the geosat since the beacon is not an absolute position reference. The combination of the tip-tilt and deformable mirror control loops can correct the star light or outgoing laser beam to about 50% of the diffraction limit.

Component technologies for the adaptive optics system have been developed to within an order of magnitude of what is required for the power beaming application. Deformable mirrors with 500 subapertures are available and high speed wave front sensors and reconstruction computers with 300 channels have been tested. Tip-tilt sensors and mirrors which are adequate for power beaming already exist. With the rapid pace of technology advancement in these areas, it is reasonable to assume that the order of magnitude improvement needed will be forthcoming in the next few years.

6. POWER BEAMING SYSTEM

At this point, the numerous aspects of a power beaming system can be assembled to arrive at preliminary point design in the following manner:

- 6.1. **Laser Average Power:** Assuming a spectral enhancement of a factor of 3 at 850 nm, the laser must deliver about 500 W/m² to match the solar flux. An overall beam transport efficiency of 50% is assumed and Eq. 1 is used to calculate the average laser power as a function of beam director diameter in Fig. 9. A band of 10-100% of the equivalent solar flux is calculated to anticipate possible trade studies which indicate that less than 100% of the equivalent solar flux may still improve the battery lifetime significantly.

Figure 9. Operating scenarios for laser power beaming.

For the geostationary orbit, hundreds of kilowatts are needed with a 3 meter beam director. However, for the new series of 8-10 meter telescopes presently being built, only tens of kilowatts are needed. Such a system would have an interesting dual use capability since power beaming to geosats is only possible for a few months out of the year and the 10 meter telescope with adaptive optics capability would be in great demand for astronomy. Indeed, the idea of building a 10 meter, corrected telescope which can generate revenue far in excess of its operating budget is unique. For a demonstration facility, a few kilowatts of laser power and a one meter beam director could also deliver an equivalent solar flux to a 300 km low earth orbit satellite.

- 6.2. **Laser Wavelength and Pulse Format:** For a near term demonstration, various wavelengths including 1.06 μ can be used, but for the full scale system, 850 nm is optimum unless other solar cell materials can be developed. The optimum laser format is CW, at least for the present generation of solar cells, but duty cycles of no less than a few percent can be tolerated.

- 6.3. **Beam Director:** The advantages of a larger beam director in terms of lower laser power is clear from Fig. 9. For the 8 meter case, the spot size at geosynchronous orbit is about 10 meters at 850 nm and the pointing accuracy is about $0.5 \mu\text{rad}$ for a 3 meter solar cell. For the 3 meter beam director, the spot size is 27 meters and the pointing accuracy is about $5 \mu\text{rad}$. The issue here is the cost and technical risk of a large beam director versus those of a higher power laser system. Three meter beam directors do exist and their cost is of the order of \$30 M, whereas lasers in the hundreds of kilowatt range do not exist and laser power is wasted due to overfilling. Several large telescopes in the 8 meter class are being built at costs in the \$60 M range and the second Keck is expected to cost \$80 M. While laser systems in the 30 kW range (which would be required) do not exist either, visible laser systems have been built in the 10 kW range at LLNL. While these lasers are not appropriate for power beaming, LLNL is learning how to build and operate high power laser systems which are within a factor of 3 of what is required for power beaming.
- 6.4. **Adaptive Optics System:** Assuming an 8 meter beam director and a moderate site, the number of channels in the adaptive optics system is about 1500 and an order of magnitude less for a 3 meter beam director.
- 6.5. **Beacon Laser Power:** The beacon laser power per spot scales roughly as r_0^{-3} , but at 850 nm, a single spot can only correct about a 2 meter telescope. This effect is due to the finite isoplanatic angle of the atmosphere. For a 3 meter telescope, a few beacons are needed, and for an 8 meter telescope, approximately 12 beacons are needed. For the new generation of high quantum efficiency CCDs, the laser power per beacon is about 30 watts so that the total beacon laser power for the 3 meter and 8 meter beam directors is about 100 watts and 400 watts, respectively.

7. CANDIDATES FOR THE POWER BEAMING LASER

Several candidate laser systems have been proposed for a power beaming laser. The earliest proposal from NASA, aimed primarily at the lunar mission (which requires 10 megawatts), relied on an Induction Free Electron Laser (I-FEL) developed at LLNL. This laser has a duty cycle of 0.01% and is inappropriate unless new solar cells, which can handle high peak powers, are developed. The most promising candidate at this time for high average power appears to be the RF-FEL which can have an acceptable pulse format when fully developed. At present, however, RF-FELs operating in the visible range have produced average powers no greater than 10 watts so a lengthy development phase is required. Nuclear pumped lasers have also been considered, but the need for a nuclear reactor, low power per aperture, and poor beam quality also point to a lengthy development cycle. Solid state lasers, especially those pumped by high power diode array, are a definite possibility in the 30 kW range, but hundreds of kilowatts will also require lengthy development. The LLNL copper vapor laser pumped dye laser system developed for isotope separation has already produced kilowatt average powers and is ready for a near term demonstration. Designs exist for 30 kW dye laser systems but this technology may not be cost effective. Other laser technologies in the near IR, such as CO_2 , CO and chemical laser such as HF and Chemical Oxygen Iodine Laser (COIL), have produced high average powers with high duty cycle, but the wavelength is outside the solar cell response range.

8. NEAR TERM DEMONSTRATION

It is very important to demonstrate the overall system aspects of power beaming as soon as possible if strong commercial backing is to be assured. It is possible to field a near term demonstration at the kilowatt level using a low earth orbit satellite and the Laser Guide Star Propagation facility at LLNL. A full scale system, based on an 8 meter beam director, conventional adaptive optics system and 30 kW laser, is also possible on a longer time scale using solid state lasers and this topic is discussed in a companion paper in these proceedings.⁸

For the LLNL dye laser system, there are approximately two kilowatts of dye laser power left over after the beacon requirements are met. That laser power can be left at its present wavelength, $\approx 600 \text{ nm}$, or tuned to 850 nm at a power level of one kilowatt. As part of the Laser Guide Star Project, there exists at LLNL a 50 cm telescope which can be upgraded (for high slew rates) and be used as the high power beam director. In addition, a smaller beam director for the beacon laser and all the necessary radars, visual observers and FAA permits exist. An optical satellite tracking system has recently been delivered to LLNL as part of another program which provides the capability of controlling the two laser beam directors used in this demonstration. A diagram of the facility is shown in Fig. 10. Both power beaming and beacon lasers are transported to an underground vault from the laser building through evacuated tubes. Control loops for pointing and centering, wave front control, wavelength modulation, and stabilization are in place as routine operating systems for the isotope separation project. Both beams would be transported out of the vault and separated with a high power dichroic element to beacon and power beaming beam directors. An adaptive optics system, based on a 127 actuator, LLNL deformable mirror is already in the prototype stage and will be tested on the 3 meter Shane telescope at Lick Observatory at Mt. Hamilton, California. The one kilowatt power beaming laser delivers an equivalent solar flux to a satellite in low earth orbit at about 300 km.

Figure 10. Near term feasibility demonstration for laser power beaming.

Although many parts of such a system have been demonstrated previously in separate experiments, this would be the first integrated demonstration at a sufficiently high power level to test important system aspects. Propagation of an atmospherically corrected beam through the atmosphere at a kilowatt level, charging of solar cells on a satellite at an equivalent solar flux, tracking of a leosat with a laser beam director, and sodium beacon correction are all concepts which must be demonstrated together in order to assure continued interest and funding.

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