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26-939801

UCRL-ID-115267

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September 22, 1993

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Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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Laser Power Beaming for Satellite Applications

Herbert W. Friedman

Background

A serious consideration of laser power beaming for satellite applications appears to have grown out of a NASA mission analysis for transmitting power to lunar bases during the two week dark period.¹ System analyses showed that laser power beaming to the moon in conjunction with efficient, large area solar cell collection panels, were an attractive alternative to other schemes such as battery storage and nuclear generators, largely because of the high space transportation costs. The primary difficulty with this scheme is the need for very high average power visible lasers. One system study indicated that lasers in excess of 10 MW at a wavelength of approximately 850 nm were required. Although such lasers systems have received much attention for military applications, their realization is still a long term goal.

In the course of these lunar analyses, it was suggested that a mission to recharge batteries of satellites in geostationary orbits (geosats) might be a commercially viable application which could be achieved with laser systems only slightly 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 moderate power lasers with modern, large aperture telescopes and laser guide star adaptive optics systems, present day communications satellites could be targeted. Using higher power laser systems, but still well below those envisioned for military applications, another class of satellite applications could be addressed. These applications include orbital maneuvers and transfers using ion thrusters powered by electricity generated by laser power beaming. These satellite missions provide a convenient path of technology growth which allow for near term applications with present day satellites at moderate power levels and longer term applications requiring new satellite technology and higher laser powers.

Geostationary Communications Satellites

Geosats provide continuous worldwide coverage for telephone, television and data transmission. International regulations permit satellite orbits at 2 degree intervals and presently 159 out of the possible 180 slots are occupied. Although the size and type of geosats vary widely, the newer vehicles carry 24 transponders with an average revenue of \$2 M/transponder/year for a total industry wide revenue potential of over \$7 B/year. This is clearly a market with a large revenue stream and a laser application which can impact this market has a potential to profitably bear the large costs associated with lasers, telescopes and adaptive optics systems.

These communications satellites use solar cell arrays to power the transponders and provide housekeeping functions. The size of the solar cell arrays is based upon the solar flux constant 1370 W/m^2 and the conversion efficiency of approximately 10%. The size of these arrays are several square meters yielding power levels in the several kilowatt range.

Although geosats do receive solar flux 24 hours a day under most circumstances, there are two periods during which eclipses occur. These periods are at the spring and fall equinox, as indicated in Fig. 1. The eclipse periods last for about 30 days each with maximum darkness lasting about 72 minutes. Although these two periods account for 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.

Figure 1. Eclipse condition of a geostationary satellite at the spring and fall equinox.

The primary limitation for geosat lifetime is not battery lifetime but rather the gas supply for the thrusters which maintains a geostationary position. As shown in Fig. 2, a geosat does not remain perfectly stationary with respect to a point on the earth's surface. Gravitational anomalies cause the satellite to wobble in both the East-West and North-South directions. These orthogonal motions combine to form small Lissajous or "figure 8" patterns when viewed from the earth. Since tracking capabilities for ground stations are costly, geosats carry gas thrusters which are periodically pulsed to maintain a stationary position. It is the gas supply for this "station keeping" activity which usually limits the useful life of the satellite.

Figure 2. Station keeping dynamics for geostationary satellites.

Recently a new mode of operation² has been implemented which promises to increase the lifetime of the gas thruster supply by an order of magnitude. By simply turning off the N-S gas thruster and allowing the plane of the geosat to oscillate in the North-South direction, the thruster gas supply is extended. E-W station keeping is maintained to keep the satellites correctly separated from each other. Since the N-S station keeping mode requires an order of magnitude more gas than the E-W mode, the lifetime of the satellite can be extended significantly. This is true for satellites presently in orbit as well as those to be deployed in the future. Comsat has developed an inexpensive and reliable tracking system which makes this inclined orbit mode of operation economically viable to the user community. This tracking system is retrofitted to ground station dishes up to several meters in diameter allowing them to follow the satellite motion.

As an inducement to the user community to join in this venture, Comsat has offered a 50% reduction to users (reflecting the increase reliability risk due to prolonged operation of the remaining subsystems). Comsat plans to convert 22 geosats to this Extended Life Service. At a transponder revenue of \$1 M/year and 24 transponders/satellite, the 22 geosats produce a revenue stream of \$500 M/year. Furthermore, since these satellites are nearing the end of their normal life, the cost of the satellite has been amortized and only a small operating cost (\$1 M/year/satellite) remains yielding a net profit of about \$500 M/year. It is clear why Comsat has expressed such enthusiasm for finding a mechanism such as laser power beaming to extend the lifetime of batteries, which is the next subsystem scheduled to fail.

The mission requirements for battery charging are relatively straightforward. A single laser site can access 5-6 geosats during the period of a single eclipse. The laser must supply a fraction of an equivalent solar flux during the eclipse period with high reliability and availability. An equivalent solar flux is flux of monochromatic light which produces the same electrical output as the broad band solar flux. The fraction of equivalent solar flux 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.

Orbital Dynamics and Laser Accessibility

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 3 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 3. Satellites in geostationary orbit at the equinox.

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 $(17.3/360)$ 24 hours or about 70 minutes.

Figure 4 shows a flat projection of the earth with longitudinal lines spaced at 30 degrees. At the bottom of the figure is a compilation³ 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 4. Number of geostationary communications satellites.
(Reference: Interavia Space Directory, A. Wilson, ed. 1991-1992)

If 100% duty cycle per satellite is required, then more beam directors would be required to access more geosats since the field of view of a typical large telescope is considerably narrower than 2 degrees. If full duty cycle is not required by the batteries, then the beam director could slew to different geosats. If the average power delivered to each geosat is required to be an equivalent sun then, of course, the average laser power would need to be increased by the number of satellites. In this case the laser power delivered to a geosat averaged over the illumination time would be increased by a factor equal to the number of geosats serviced but solar cells can handle irradiances larger than one sun. (If the laser is pulsed, then there is an additional peak power enhancement equal to the inverse of the laser duty cycle.)

Another alternative, which may reduce the installation cost significantly, would be to install more than one telescope at a site. As described later in this report, the Large Binocular Telescope, to be built in Arizona, will house two telescopes on a common mount. This arrangement will double the number of accessible satellites (at double the laser power) with many shared facility costs.

Orbital Transfer and Maneuver Applications

Two other satellite applications may be economically feasible using efficient high power laser systems. The first is orbital transfer as illustrated in Fig. 5. The normal mode for launching geosats is to carry them to low earth orbit (LEO) using vehicles such as the shuttle. A rocket strapped to the satellite is then fired, propelling the satellite into a highly elliptical orbit. At the apogee of the orbit, the rocket is fired again to circularize the orbit into a geostationary earth orbit (GEO). This method is the most efficient in terms of total energy expended and the quickest in terms of time spent in the transfer orbit. This latter point is important since the orbital transfer maneuver requires the satellite to pass through radiation belts which degrade the solar cells.

Figure 5. Orbital transfer from low earth orbit to geostationary orbit.

The concept of using a rocket to effect the orbital transfer has risk both in terms of graceful and catastrophic failure. In the graceful failure mode, the rocket fails to fire and the satellite is left in a useless LEO. In the summer of 1992, such a failure occurred and NASA made a shuttle visit (at a cost of \$100 M) to strap a new rocket onto Intelsat VI. The cost of the replacement rocket was \$50 M and its weight was three times that of the payload. This weight penalty arises from the fact that the energy required to attain GEO is almost equal to that needed to escape altogether. In the catastrophic failure mode,

either the rocket explodes or malfunctions putting the satellite into a useless and inaccessible orbit. In both cases, the satellite is lost.

An alternate method of transferring a satellite from LEO to GEO is to apply power gradually and spiral the satellite into GEO, as shown in Fig. 5. Advanced ion thrusters accomplish this spiral maneuver but this concept suffers from the lack of sufficient electrical power on board. Power is limited by the solar flux constant and the size of the solar cell arrays. For present satellite technology, the time required to spiral out to GEO is six months to a year. During that time the satellite passes slowly through the radiation belts and solar cells are damaged beyond the allowable limit. An incident laser flux equivalent to ten times the solar flux would be sufficient to propel a satellite to GEO using this spiral maneuver in a time scale of about one month, the upper limit for allowable radiation damage. The economics of such a laser power beaming mission depends upon the satellite dynamics, number of lasers necessary to track the satellite during the spiral transfer, etc., and these mission studies have yet to be done.

A slightly different application of laser power beaming to satellite maneuvers would be to move satellites within a given orbit to a different plane. This maneuver is routine for military satellites on intelligence gathering missions and is accomplished using the same gas thruster technology as in station keeping for geosats. Again, the life of the satellite is determined, in part, by the gas load carried on board. Since the cost of such military satellites is very high, any technology which can extend the lifetime can be of significant economic value. The same comments regarding the need to do mission analyses apply for this application although the ground rules may be different.

Laser Power Requirements

In the absence of a 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), Eq. 1 is used with a typical value of the atmospheric transmission of 0.85, a wavelength of 850 nm 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. For the solar constant of 1.37 kW/m², Eq. 1 predicts a laser power level of about 600 kW. It will be shown below that several factors can lower this power level substantially 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 over an order of magnitude higher than the highest power visible laser system, at least in terms of a system operation for long periods of time, with high reliability and availability as would be required by a power beaming system. For the orbital transfer application where 10 suns are required, the laser power level is in the megawatt range and for the lunar mission, in the tens of megawatt range.

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. 6. 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.

Figure 6. Conversion efficiency of several solar cell materials as a function of illumination wavelength.

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. Since only silicon solar cells are in use in geosats, the maximum laser wavelength is of the order of a micron corresponding

to undamaged silicon cells. A widely used wavelength for solid state lasers is $1.06\ \mu$ for which the peak conversion efficiency is down from the peak by about a factor of 2. This wavelength could be used for a demonstration but shorter wavelengths will be needed for an operational system. It is likely that GaAs solar cells will be widely used in the future. This material has a higher conversion efficiency and solar cells using GaAs have been fabricated into "concentrator" arrays able to efficiently convert average fluxes far in excess of one sun. For this material, the optimum wavelength is approximately 850 nm.

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. 7. Since the normal range of conversion efficiency for broad band solar irradiation is in the 10-20% range, there is a factor of about 3 to be gained using monochromatic light. The laser need only supply approximately $500\ \text{W}/\text{cm}^2$ at the satellite orbit to match the sun.

INTENSITY = $500\ \text{mW}/\text{cm}^2$ TEMPERATURE = 25°C

Figure 7. Theoretical conversion efficiency of photovoltaic cells for monochromatic light.

The spectral response curves shown in Fig. 6 relate to new solar cell material which have not been exposed to the space radiation environment. The effect of solar radiation damage has been simulated in the lab using high energy beam electrons. Examples of the changes in the spectral response for two silicon solar cells is shown in Fig. 8⁴. The conversion efficiency drops, the long wavelength performance decreases, and the optimum wavelength shifts to the blue. The curves are plotted parametrically as a function of electron dose with $10^{15}\ \text{e}/\text{cm}^2$ corresponding to a lifetime at geosynchronous orbit of 30 years. The lifetime is linear with dosage so that the typical geosat lifetime of

ten years corresponds to the data between the 10^{14} - 10^{15} e-/cm². The data indicates that operation at the popular solid state laser wavelength of 1.06 microns for ten year old radiation damaged solar cells is only 20% as efficient as if 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.

Effect of radiation damage on the spectral response of a silicon solar cell.

Spectral response from a 10Ω-cm silicon solar cell as a function of wavelength for various 1-MeV electron irradiation levels.

10^{15} e-/cm² corresponds to roughly 30 years in geosynchronous orbit (depending on shielding).

Reference: G. Landis, NASA Lewis Research Center

Figure 8. Conversion efficiency for radiation damaged silicon solar cells.

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 completed⁵ 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 of the study can be extended to provide insight to other lasers as well.

The I-FEL pulse format is characterized by a pulse train consisting of regularly spaced pulses with duration of several tens of nanoseconds with a repetition frequency of approximately 10 kHz. This pulse format has a duty cycle of the order of 5×10^{-4} , or a peak to average power ratio of 2000. The impact of the low duty cycle is that for a average power of one sun incident upon the solar cell, the peak power is 2000 suns. 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.

The pulse format of the RF-FEL is more complex, consisting of a burst of micro pulses. The micro pulses have a duration of tens of picoseconds and a repetition rate in the megahertz range. The burst or macropulse lasts about a hundred microseconds and, at present, are repeated at a very low rate due to the lack sufficient thermal control. In the future, the RF-FEL designs call for a high macropulse repetition rates reaching near continuous operation. In some designs, the duty cycle can be 5×10^{-3} and the peak to average enhancement is only 200. Furthermore, due to the finite capacitance of the solar cell and the internal resistance, the minimum response time of the cell is approximately a nanosecond, i.e., the cell integrates pulses shorter than a nanosecond so that the effective pulse is longer. Under these conditions, the peak to average enhancement is a few tens.

Due to the lack of availability of any FEL routinely operating in the visible, the two FEL pulse formats were simulated by other lasers. At LLNL, a copper vapor laser with a 50 ns pulse duration operating at about 10 kHz was used to simulate the I-FEL. At Rocketdyne Corp., a mode locked, frequency doubled YAG laser simulated the RF-FEL. The results of these tests are listed in Fig. 9. Both lasers operated in the green portion of the spectrum and the results scaled to the optimum wavelength based upon the spectral curves of Fig. 6. The dependence of the conversion efficiency on wavelength is sufficiently well known, even if this dependence has not been confirmed under identical pulse formats, so that wavelength scaling is adequate. Clearly, these results must be repeated at the correct wavelength under pulsed situations before a final design for a laser system should be completed.

The column marked AMO refers to broad band solar radiation and the conversion efficiencies lies primarily in the 10-20% range. Using a CW argon ion laser at 574.5 nm and scaling the results to the optimum wavelength, the conversion efficiency increases over the broad band value by about a factor of two. The results of the two different pulse formats show that the low duty cycle, I-FEL simulation are lower than the CW result by considerable amounts whereas the high duty cycle, RF-FEL results track the

monochromatic CW results considerably better. These results represent the first attempt at a systematic study of the effects of peak power on conversion efficiency and are very sketchy. The trend is clear and points to a peak to average enhancement of no more than 100 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.

Cell technology	Corrected experimental results (at ~1 Sun for all; at 840 nm for lasers)									
	AMO	Continuous wave laser	Pulsed RF FEL simulation	Induction FEL simulation						
Planar cells										
• Silicon	16%	31%	—	13%						
• Gallium arsenide	20%	47%	—	<1%						
Concentrator cells										
• Silicon	15%	25%	19%	21%						
• Gallium arsenide	21%	43%	2% ^c	3%						
Unique cells/tests										
• Silicon planar (radiation damaged) ^a	11%	23%	—	4%						
• Gallium arsenide concentrator (capacitor) ^b	19%	35%	44%	7%						
<table><tr><th>Cell technology</th><th>Advanced laser cell technology efficiency goal</th></tr><tr><td>Silicon</td><td>45%</td></tr><tr><td>Gallium arsenide</td><td>60%</td></tr></table>					Cell technology	Advanced laser cell technology efficiency goal	Silicon	45%	Gallium arsenide	60%
Cell technology	Advanced laser cell technology efficiency goal									
Silicon	45%									
Gallium arsenide	60%									

Notes:

^aSilicon planar (radiation damaged) has been exposed to 5E+14 1 MeV electrons per centimeter square

^bGallium arsenide concentrator (capacitor) has a 4.4 microfarad capacitor across cell during FEL simulation tests to measure the effect of smoothing high laser peaks

^cEstimated from tests performed on similar cell

Reference:

B. Anspaugh et al., "Results of Illuminating Various Solar Cells With Laser Beaming, NASA, JPL-92-25, November 1992

Figure 9. Preliminary summary of photovoltaic cell conversion efficiency.

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 of the atmosphere⁶, r_0 , is the largest dimension over which the wave front of an otherwise coherent source at infinity, can be represented by a plane wave. The plane wave front over an r_0 scale may have a tilt but the wave front is sufficiently flat such that the departure of the wave front from flat is less than $1/20$ wave in an RMS sense. The " $1/20$ wave" criterion is generally taken to mean diffraction limited since the on axis intensity of such a wave front at focus is greater than 90% of the diffraction limited value, i.e., the so-called Strehl ratio. The wave front of a coherent object at infinity falling on the aperture of a telescope (or beam director) which is larger than r_0 may then be represented by a piece wise linear curve of randomly tilted sections with the dimension of the linear portion equal to r_0 .

Since the propagation of light is reciprocal, it follows that the divergence of a laser beam through the turbulent atmosphere is increased by the ratio of D/r_0 and therefore that the intensity of the laser beam at the satellite orbit is decreased by the ratio of $(D/r_0)^2$. The quantity r_0 is a function of the atmosphere along the beam path and of laser wavelength. At the 850 nm value, typical values of r_0 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 r_0 are not the largest values observed but represent the median over long times as would be appropriate for power beaming.

The effect of the parameter r_0 on the complexity of a adaptive optics systems used to counteract the beam spreading caused by atmospheric turbulence occurs in several ways. First, the number of channels of a closed loop, adaptive optics system scales approximately as the ratio $(D/r_0)^2$ and the bandwidth of the control loop scales approximately as (V_w/r_0) where V_w is the wind velocity. Hence, for a large telescope at moderate sites, the number of control channels can be several thousand and the bandwidth of the control system can be several hundred Hertz. Furthermore, the rate at which the wave front needs to be sampled in order to get accurate statistics for wave front correction is about ten times the closed loop bandwidth so that the wave front sample rate can easily be of the order of a kilohertz. Moving to a better site can significantly reduce the complexity of an adaptive optics system but this benefit has to be balanced by the logistics of construction and operation at the top of a mountain.

The method of correcting the power beaming laser involves sensing the wave front distortion from a beacon in the satellite path and controlling a deformable mirror in the optical train of the laser so as 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 either laser scattering off the upper edge of the atmosphere (Rayleigh scattering off density fluctuations) or resonant scattering off of metallic atoms in the mesospheric layer. The height of the Rayleigh scattering layer is about 10 km, whereas the

mesospheric layer exists at about 100 km. Since the path of the beacon return from the mesospheric layer more closely approximates the parallel propagation path of the power beaming laser than does the Rayleigh beacon, the mesospheric beacon yields a better correction to atmospheric turbulence.

Sodium atoms have been suggested⁷ as a bright fluorescent source for a beacon and several groups⁸ have made measurements of sodium-layer laser guide stars. A group at LLNL⁹ has generated the brightest sodium-layer laser guide star using a powerful laser developed for Isotope Separation and plans to close a control loop, as shown in Fig. 10, in the fall of 1993.

Figure 10. Conceptual design of the LLNL laser guide star control system.

Aside from the number of channels needed for the control system hardware, the laser power needed to generate the sodium-layer guide star depends strongly on the parameter r_0 . The number of photons in the return signal for the wave front detector is a fixed number per subaperture of r_0^2 dimensions, with the actual number dependent upon the detector sensitivity. The rate at which the wave front must be sampled also depends upon $1/r_0$ so that the total laser power scales as r_0^{-3} . For a moderately good site where $r_0(\lambda=850 \text{ nm}) = 20 \text{ cm}$, the laser power required to achieve a Strehl ratio of 0.5 for a 3 meter and a 10 meter telescope is of the order of 100 watts and 500 watts, respectively. The difference between the two beam director apertures comes from the need to provide additional beacons for the larger aperture to correct for the cone effect of the finite altitude of the beacon.

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 11 shows a 1100 watt laser beam propagated upwards from the LLNL site. Figure 12 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 required by the adaptive optics system for a good beacon. Figure 13 shows a series of photographs of the Rayleigh scattered beam with the sodium guide star appearing as a round dot at the top. These photographs were taken at a distance of five meters from the laser launch point.

The laser system which generated the beam shown in Fig. 11 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. 14. 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

Figure 11. Propagation of the LLNL 1100 watt laser beam tuned to the sodium wavelength.

Figure 12. Sodium laser laser guide star photon applied at a distance of four miles from the propagation site

Laser PRF = 26 kHz, pulse duration = 50 ns

Figure 13. Photographs of the Rayleigh plume and laser guide star taken at various laser power levels.

Figure 14. AVLIS laser system design concept.

copper and dye laser systems is shown in Figs. 15 and 16. It is to be noted that 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. This concept will be described in detail later.

Figure 15. Power output of the copper vapor laser system.

Figure 16. Power output of the dye laser system.

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. 17. 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. The choice of distance between the sodium laser beam director and the main telescope is a trade off between the elongation of the sodium beacon, which reduces wave front sensor accuracy, and the size and alignment of the blocking pinhole. The discrimination scheme is based purely on angular separation and not dependent upon the sodium laser pulse repetition rate. The isotope separation laser has a pulse repetition rate of 26 kHz and the return signal appears as quasi CW because there is always a pulse in the sodium layer.

Figure 17. Detailed design of the LLNL laser guide star optical system.

There are other configurations for the sodium laser. Lincoln Laboratory¹⁰ has pioneered the development of a solid state laser system consisting of two Nd:YAG lasers tuned to $1.06\ \mu$ and $1.3\ \mu$. These are mixed in a crystal and a fortuitous coincidence occurs between the sum frequency signal and the sodium wavelength. This laser operates in a complex mode locked, burst mode at a kilohertz which allows the sodium laser beam to be co-propagated through the main telescope as shown in Fig. 18. Unwanted Rayleigh scattered light is rejected by a time gating scheme which is possible due to the low pulse repetition rate of the laser. Such a co-propagation scheme is not always favored for astronomy because of the low light levels of the astronomical objects of interest but is acceptable for power beaming.

Figure 18. Common path optical configuration.

A hybrid scheme also exists whereby the sodium laser is mounted on the Naismith or coude platform of the main telescope. The beam is passed through the bearings and tucked behind the secondary mirror of the telescope. In this way the laser beam does not reflect from the telescope optics but shares the azimuth and elevation bearings so that a separate beam director is not needed. The laser beam path can be enclosed in a tube to avoid the stray light problem. Rayleigh scattered light is rejected by a combination of angular acceptance (the secondary mirror of the telescope blocks the Rayleigh beam at low altitudes) and possibly range gating if the secondary mirror is not sufficiently large.

Another type of laser is currently being developed wherein the copper vapor laser pump source is replaced by a solid state laser, a frequency doubled Nd:YAG. The dye laser is retained as the frequency converter because of its high conversion efficiency at high average power and good beam quality. For lower sodium laser power levels, the solid state pump laser has definite advantages over the copper vapor laser, whereas for high power levels, the situation is still unclear. Currently, the solid state laser is flashlamp pumped, but as the cost of diode lasers decreases, diode pumping will likely be the preferred mechanism.

Referring to the control system diagram of Fig. 17, return light from the beacon and the astronomical object of interest enter the pupil of the telescope and pass through the pinhole where the Rayleigh scattered light is filtered out. Both beams reflect off a tip-tilt and deformable mirror and onto a dichroic mirror. The beacon light is passed into a wave front sensor and the star light is reflected to the science camera. Information from the wave front sensor is fed into the wave front reconstruction computer and a set of drive signal is applied to the actuators of the deformable mirror closing the main control loop. Information for the tip-tilt sensor is derived from a glint off the geosat. It is not presently possible to use the laser beacon for tip-tilt information (or tracking as it is sometimes called) because the position of the guide star is not fixed in space. Since the beacon laser passes through the atmosphere on the uplink, the position of the guide star can wander and, therefore, it is not suitable for tracking information.

The combination of the tip-tilt and deformable mirror control loops correct the star light or outgoing laser beam to a degree dependent upon several parameters such as beacon laser power, number of wave front sampling subapertures, detector noise, etc. In a practical sense, correcting the laser beam to a Strehl of 0.5 is reasonable at 850 nm. Higher corrections require much larger beacon lasers, more subapertures, better detectors, etc., and the final system configuration results from a trade off among all these parameters, however, a Strehl of 0.5 is a reasonable value for an initial system evaluation.

For the power beaming application, the "science camera" of Fig. 17 is replaced by the power beaming laser and conceptually, all other system components remain otherwise unchanged. There is an issue of the source for the tip-tilt sensor since there may not be a bright natural guide star close enough to a geosat for this purpose. For geosats, it is sufficient to use a glint from the satellite itself. The round trip time to geosynchronous orbit is approximately 120 ms during which time the satellite moves approximately 2 arcsec. This angle is within the isoplanatic patch, especially for the low frequency tip-tilt correction and the entire telescope aperture can be used as a collector. Thus the satellite glint can serve as a tip-tilt sensor. The glint is not sufficient to serve as a source for the high (spatial frequency) wave front sensor because the return signal is too weak.

Other components in the adaptive optics control system will challenge the state-of-the-art for a power beaming application. The wave front sensor is usually either a shearing interferometer or a Shack-Hartmann lenslet array. There are other wave front sensors but none have been shown to scale to large telescope apertures. LLNL has developed and built Shack-Hartmann sensors for the isotope program using commercially available lenslet arrays from Corning and is using this hardware in the Laser Guide Star Program. A shearing interferometer has also been purchased from Itek Corp. and is presently being tested in a comparison scheme with the Shack-Hartmann technique to determine relative advantages of each. Shearing interferometers have the advantage of allowing variable shear to match atmospheric conditions in an optimum manner whereas Shack-Hartmann lenslet arrays are fixed devices. Shack-Hartmann sensors are very efficient with regard to light collection efficiency. The result of these trade studies will quantify both systems.

The computer system which converts wave front information into a set of drive signals for the deformable mirror was a source of some concern at the beginning of adaptive optics programs. Hardware and software was insufficient for the task and as a result some complex hardware and software (machine language) was used. These proved to be very user unfriendly and were difficult to modify. Computer technology has advanced rapidly and LLNL now uses commercial based hardware (Sun Sparc workstations, Mercury parallel processor boards using Intel I860 microprocessors, etc.) and user friendly software for wave front reconstruction. As the number of channels in the adaptive optics system increases, this problem will again arise and it is important to maintain commercial based systems with user friendly interfaces.

The deformable mirror is the heart of the adaptive optics system. Several companies have developed high speed deformable mirror systems for the military application of power beaming but these mirrors are very expensive as a result of the stringent requirements for military missions. For example, power beaming to leosats requires high bandwidths, i.e., kilohertz, to account for the apparent wind which results from the high slew rates. High average power for material damage requires cooled mirrors to maintain optical quality. The need to operate in non optimal environments with essentially 100% availability necessitates large numbers of channels to match the small values of r_0 likely to be encountered.

Several companies offer deformable mirrors for sale including Itek Corp. (Lexington, MA), United Technologies (West Palm Beach, FL), Bell Aerospace (Buffalo, NY) and Thermotrex (San Diego). LLNL is presently using an Itek mirror with 69 actuators in an adaptive optics system at Lick Observatory and other Itek mirrors have been used by Lincoln Laboratory and Air Force Phillips Laboratory with up to 241 actuators. United Technology and Bell Aero have developed cooled deformable mirrors for high power applications and Thermotrex has developed a 500 segment mirror for Navy and astronomical applications.

The cost of presently available deformable mirrors is prohibitive for astronomical applications and LLNL is developing a deformable mirror based on low cost designs originally developed for isotope separation. Examples of a low cost deformable mirror, funded by the University of California specifically for astronomy, are shown in Fig. 19. The small mirror, which is a prototype of larger designs, has 19 actuators and is being used in a closed loop experiment at LLNL due to be completed in the fall of 1993. The larger substrate contains provisions for 127 actuators and will be used first on the 3 meter telescope at Lick Observatory. This design concept will scale to approximately 1000 channels which will be needed for large telescopes, such as the Keck 10 meter, either for astronomy or for power beaming. Present cost for the LLNL technology are in the \$300/actuator range whereas the military version are roughly an order of magnitude higher.

For the astronomy application, power densities on the deformable mirror are, of course, not a concern. This is not obviously true for power beaming. The isotope program has developed very low loss coatings with absorption of the order of 10^{-5} . This low absorption value permits maximum average power densities of approximately 10 kW/cm². For power beaming applications, laser powers of up to 500 kW can be safely handled by 10 cm diameter mirrors. The LLNL mirror technology can be scaled to substrates of approximately 30 cm in diameter so that cooling is not required.

Figure 19. 19 actuator deformable mirror to be used in the laser guide star optical system.

Other important technologies are the tip-tilt sensor and tip-tilt mirror. The isotope program at LLNL has developed a sensitive tip-tilt sensor consisting of an avalanche photodiode, quad cell detector, and thermoelectrically cooled, stabilized circuit. For the astronomy application, a small, piezoelectrically driven tip-tilt mirror available commercially is adequate. For the power beaming application, the isotope program has developed a 6 inch tip-tilt mirror capable of handling high average power. This mirror has demonstrated a bandwidth capability of one kilohertz at a cost which is substantially less than the military version.

Power Beaming System

At this point, the numerous aspects of a power beaming system can be assembled to arrive at preliminary point design. Although there are significant uncertainties in several of the system parameters, a complete listing is still useful to focus attention of the system concept.

- A. **Laser Average Power:** The basic criteria is to deliver one equivalent solar flux to a object in space at a given distance from the earth. The solar flux constant is 1.37 kW/m^2 , but as shown in Fig. 6, a monochromatic beam is more efficient than broad band solar radiation. It is assumed that the enhancement factor for monochromatic light is approximately a factor of 3 so that only 500 W/m^2 are needed. An overall beam transport efficiency of 50% is also assumed to account for the departure of the beam divergence from diffraction limited and the ability of the adaptive optics system to fully correct for the effects of turbulence. Equation 1 is used to calculate the average laser power needed to deliver laser flux to space at a wavelength of 850 nm and the result is shown in Fig. 20 for three different space positions, low earth orbit, geostationary orbit, and the lunar surface. A band of powers are shown as well to indicate the laser powers to deliver between 10% and 100% of an equivalent solar flux. This last point addresses the system issue that there may be a trade off between the flux delivered and the battery performance, i.e., batteries may not need to be fully charged to extend their life significantly and somewhat less than 100% of equivalent solar flux may not be required to realize large system benefits.

Figure 20. Operating scenarios for laser power beaming.

For the geostationary orbit, a few hundred kilowatts are needed with a 3 meter beam director. However, for the new technologies of large astronomical telescopes, only a few tens of kilowatts are needed for 10 meter beam directors. 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 have use for astronomy. Indeed, the idea of building a 10 meter, corrected telescope which can bring in 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. Larger beam director would require even less power but the spot size becomes smaller than the satellite. The major difference between low earth orbit and geostationary orbits is the need to track through high slew rates, an added complication but one which is within state-of-the-art for small beam directors.

- B. Laser Wavelength and Pulse Format: Although a near term demonstration can be meaningful at various wavelength including $1.06\ \mu$, the long term optimum is 850 nm unless other solar cell materials can be developed. Aside from trying to match an efficient laser wavelength, shifting to longer wavelength will have added benefits in simpler adaptive optics systems since the number of channels and bandwidth are both reduced. The optimum laser pulse is CW, at least for the present generation of solar cells. Duty cycles of no less than a few percent can be tolerated so that the peak to average power enhancement is not greater than 50:1.
- C. Beam Director: The advantages of a larger beam director in terms of lower laser power is clear from Fig. 20, but the pointing and tracking accuracy must also be considered. For the 8 meter case, the spot size at geosynchronous orbit is about 10 meters at 850 nm. Assuming a three meter solar cell size, the pointing accuracy is about 0.1 arcsec, or about $0.5\ \mu\text{rad}$. For the 3 meter case, the spot size is 27 meters and for the same 3 meter solar cell array, the pointing accuracy is of the order of 1 arcsec or $5\ \mu\text{rad}$.

The trade off 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 power range of 300 kW, which would be required to deliver an equivalent solar flux at geostationary orbit, do not exist. High average power (chemical) lasers systems in the infrared region do exist but these wavelengths are not appropriate for power beaming. On the other hand, large telescopes in the 8 meter class are being built at costs in the \$60 M range. 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, the laser community 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.

- D. Adaptive Optics System: The number of channels in the adaptive optics system scales with the square of the ratio of beam director aperture and (atmospheric) turbulence correlation scale, r_0 . As a reasonable assumption, r_0 ($\lambda=850\ \text{nm}$) = 20 cm so that roughly 1500 channels are needed for the 8 meter beam director. For the 3 meter beam director, the number of channels is about an order of magnitude less.
- E. Beacon Laser Power: The beacon laser power scales mainly as r_0^{-3} , as indicated previously, but also with the size of the beam director aperture. The scaling with beam director aperture arises from the finite height of the beacon. Ray paths from the beacon to the edges of the aperture are not parallel and only a maximum angle can be tolerated before the turbulence correction is not relevant for the parallel rays of either incoming star light or outgoing power beaming laser light. The remedy for large apertures is to place several sodium beacons in the mesosphere. For the visible range at high Strehl, a single sodium beacon can service apertures up to 2 meters. For a 3 meter telescope, the number of beacons is about 4 rising to about 15 for a 10 meter aperture. Since the laser power per beacon is constant, the laser power for the large

aperture system is 4 times as much as for the 3 meter case. The laser power per beacon depends upon the sensitivity of the detector used for the wave front sensor (assuming constant r_0). For image intensified CCD cameras, about 1000 photons are needed in each subaperture of area r_0^2 . For the newer generation of back illuminated bare CCD cameras with high quantum efficiency, the number can be an order of magnitude less. For $r_0 = 20$ cm, the laser power for image intensified CCD's, the laser power is about 30 watts per beacon or 500 watts for the larger aperture beam directors.

Candidates for the Power Beaming Laser

Several candidate laser system have been proposed for a power beaming laser. The earliest proposal from NASA aimed primarily at the lunar mission (which requires 100 times the laser power) relies on an Induction Free Electron Laser (I-FEL). This laser has a pulse duration of tens of nanoseconds at a repetition frequency of tens of kilohertz or a power factor of 10^{-3} . The peak intensity of this laser is 1000 times the average power. According to the results of pulse format simulations summarized in Fig. 9, the low duty cycle is inappropriate for efficient conversion in state-of-the-art solar cells. Although there are proposals for advanced solar cells which might accommodate higher peak power, this laser is not presently considered for power beaming.

Another version of Free Electron Lasers, the RF exited FEL¹¹, does have sufficient duty cycle to efficiently convert in solar cells and this technology is the leading candidate according to a NASA study. Albeit considerable funding has been invested in both I-FEL and RF-FEL technology, the highest average power achieved in the visible region is only 10 watts. Although FEL technology shows promise for high average power operation, much work needs to be done to demonstrate this potential. In addition, although FEL lasers may be cost effective for very high average powers, this may not be the case for the low powers needed for the near term, power beaming application.

A laser system which has received some attention for power beaming is the Nuclear Pumped System¹² usually employing an excimer or excimer-like gas such as Xenon. Aside from the popular aversion to nuclear pumped applications, the laser has the serious deficiency that the average power per unit aperture is not expected to scale much beyond 1 kW. The implication is that anywhere from tens to hundreds of individual beams must be coherently added to take full advantage of a common, large aperture beam director. Such a system would require not only an adaptive optics system for the combined beam, but another adaptive optics system in order to combine the many beams coherently.

At present, there appear to be no other high power gas laser candidates for power beaming. Efficient lasers such as CO and CO₂ which emit in the near IR are unsuited for solar cell conversion. Efficient chemical lasers such as the Chemical Oxygen-Iodine Laser (COIL) and HF/DF emit closer to the visible but at too long a wavelength to be considered for present day solar cells.

Liquid lasers such as that developed for the isotope separation project have the capability to achieve several kilowatts at 850 nm and with further development could achieve high duty cycle. It is doubtful that these lasers could be scaled beyond that level in a single or few numbers of apertures and in a cost effective manner. At present their use is relegated to the beacon laser.

Several solid state lasers can be considered. The new popular host is sapphire with titanium being the dopant of choice. Sapphire has excellent thermal qualities as exemplified by its thermal conductivity which at liquid nitrogen temperatures exceeds twice that of copper. Sapphire is also a very strong material with low coefficient of thermal expansion. Furthermore, its emission region is peaked at about 800 nm so that spectrally it is appropriate. The difficulty arises with the pump requirements. With an absorption band well below 700 nm and upper state lifetime of only a few microseconds, Ti:Sapphire is not well suited to diode pumping. CW green laser pumps and flashlamps have been used but it is doubtful that high average powers will be attained. Solid state lasers can be used for pumps for Ti:Sapphire but a better alternative is to use these lasers directly as explained below.

A candidate which has high potential for a power beaming is the Diode Pumped Solid State Laser (DPSSL). The YAG host with Nd dopant has a wavelength of $1.06\ \mu$ in normal operation and other candidate hosts and dopants may operate efficiently at the desired 850 nm wavelength. Flashlamp pumped solid state lasers have operated at several kilowatts and recently, a DPSSL has produced over a kilowatt of average power. Under a new method of operation, the heat capacity mode, it should be possible to achieve several hundred kilowatts of average power. The heat capacity mode of operation strives to achieve uniform pump intensity during an extraction cycle of several seconds during which no heat is extracted out of the lasing crystal by any means other than from the lasing beam itself. Pulsing occurs during the extraction period at a duty cycle of about 10% making efficient use of the diode pumping arrays. During the extraction period the temperature of the crystal rises (uniformly) until the kinetic parameters degrade sufficiently to reduce the gain/loss ratio beyond useful operation. This point occurs at a temperature rise of about 160°C at which time the total extracted laser energy is about $800\ \text{J}/\text{cm}^3$. The lasing ceases and the heat is removed from the lasing crystal using a face cooled flow of high speed gas or a phase change mechanism using a high flow of atomized mist. The cool down cycle is calculated to last about 10 seconds for an overall duty cycle of about 2% (or a peak to average power enhancement of 50:1). At LLNL several kilojoules have been extracted from a crystal in this heat capacity mode with beam divergence of less than two times the diffraction limit. A design activity is underway to develop the configuration for a laser which will deliver up to 4 MJ in a combined extraction and cooling time of about 12 seconds for an average power of over 300 kW with a duty cycle of 2%.

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. Embarking on a long program of subsystem development on the power beaming laser, beam director, adaptive optics, etc. will not likely be funded in this present climate and will certainly be viewed with skepticism in light of past high power laser programs. It is possible to field a near term demonstration with existing hardware at LLNL.

As shown in Fig. 16, there is approximately one kilowatt of dye laser power left over after the beacon laser requirements are met. That laser power can be left at its present wavelength, ≈ 600 nm, or tuned to 850 nm which is the peak of the solar cell conversion efficiency curve. According to the data in Fig. 6, operation of the solar cells at 600 nm reduces the conversion by only 25% which is acceptable for a demonstration.

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 power beaming beam director, a smaller beam director for the beacon laser, telescopes for satellite tracking and all the necessary radars, visual observers and FAA permits to allow a near term demonstration. An optical satellite tracking system has recently been delivered to LLNL which provides the capability of controlling the two laser beam directors used in this demonstration. A diagram of the facility is shown in Fig. 21. Both power beaming and beacon lasers are transported to an underground vault through evacuated tubes. Control loops for pointing and centering, wave front control and wavelength modulation, and stabilization are in place as routine operating systems for the isotope separation project. Both beams are transported out of the vault and separated with a high power dichroic element to beacon and power beaming beam directors. An adaptive optics system on the power beaming director consists of a deformable and a tip-tilt mirror control system. This AO system uses the laser beacon as a guide star to correct the power beaming laser. The one kilowatt power beaming laser delivers an equivalent solar flux to a satellite in low earth orbit at about 300 km.

Figure 21. 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 high enough power 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.

Mid Term Demonstration

The next phase demonstration would involve use of a prototype DPSSL run in the heat capacity mode. LLNL has designed a single slab laser capable of 1 MJ extraction in approximately three seconds for an average power of 300 kW. This design does not have a short cooling cycle; the cooling cycle is of the order of one minute but the device would serve as an important demonstration continuing the adaptive optics portion but now allowing propagation to a geosat. As seen in Fig. 20, 300 kW of laser power, combined with the 50 cm beam director, delivers about 1% of solar flux to a geosat which is about the lower limit of detectability.

Another version of the mid term demonstration would involve upgrading the beam director to the 3 meter class, which although is impractical for an LLNL site, could exist at several locations in the US. The Air Force Phillips Starfire Optical Range in New Mexico, the Lick Observatory in San Jose, the new Air Force facility at Mt. Haleakala in Hawaii, are all likely locations for such demonstrations.

Long Term Demonstration

A preliminary economic analysis of a commercial power beaming system has shown that a capital cost of \$100 M would permit break even operation of a single site almost immediately. At this point in time, with laser costs uncertain, the optimum system would be a large beam director and a modest laser system. The dual use for astronomy is another advantage of such a configuration. Present cost of an 8 meter telescope is of the order of \$60 M as evidenced by the ongoing projects of the Gemini, European Southern Observatory, New Technology Telescope (Japan) and the Columbus Telescope projects. The adaptive optics cost for such a system is of the order of \$10 M assuming \$5000/channel and 2000 channels. That leaves \$50 M for the cost of the laser or about \$1500/watt for the 30 kW laser. The present cost for many high power laser systems today is of the order of \$1000/watt so that this estimate for an order of magnitude higher power system is not unreasonable.

A more attractive alternative is to form a consortium with an existing or planned telescope facility. The Columbus facility planned for 1998 operation at Mt. Graham in Arizona is an example of such a consortium. The Columbus Large Binocular Telescope pictured in Fig. 22 is a twin 8.4 meter device with ample room for a laser in the coude building below the telescope. The median value of r_0 at 850 nm is 28 cm so that 20 cm is a reasonable estimate for higher availability. The cost of entering into such a consortium, which would guarantee usage for two months per year is approximately \$7.5 M with a yearly operating cost of about \$2 M. With the AO system and power beaming laser costs as stated above, the total installation is well below the \$100 M target figure for economic profitability. Using both telescopes of the LBT, twice as many geosats could be accessed. The average laser power would need to be doubled, but many facility costs could be shared. The economic impact would be to double the revenue with less than a doubling in system costs.

Figure 22. Large Binocular Telescope Project at Mt. Graham.

Conclusion

Laser power beaming for satellite applications has a near term mission of battery charging which may be economically viable with only modest extensions of present technology. The new generation of large aperture telescopes and the rapidly growing field of adaptive optics permit solar level fluxes to be delivered to geosats with solid state laser systems which are less than an order of magnitude larger than present state-of-the-art devices. The availability of many subsystems associated with the Laser Guide Star Project at LLNL will allow a near term demonstration of laser power beaming at a power level which realistically tests the concept for a full scale system.

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