System requirements for Laser Power Beaming to Geosynchronous Satellites

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Abstract

Geosynchronous satellites use solar arrays as their primary source of electrical power. During earth eclipse, which occurs 90 times each year, the satellites are powered by batteries, but the heavy charge-discharge cycle decreases their life expectancy. By beaming laser power to satellites during the eclipses, satellite life expectancy can be significantly increased. In this paper, we investigate the basic system parameters and trade-offs of using reactor pumped laser technology to beam power from the Nevada Test Site. A first order argument is used to develop a consistent set of requirements for such a system.

1 INTRODUCTION

Several authors have presented recent papers on concepts for laser power beaming to existing satellites. Most recently Morgan and Lipinski[1] made a strong case for using reactor pumped laser technology to build a laser power beaming system located at the Nevada Test Site. The principle operation of this system would be to beam laser power to geosynchronous satellites, both military and civilian, during their eclipse periods. Their paper discussed the basic concept and some of the requirements for such a system. The purpose of this paper is to probe deeper into the basic system parameters and trade-offs and to develop a first order argument for a consistent set of requirements.

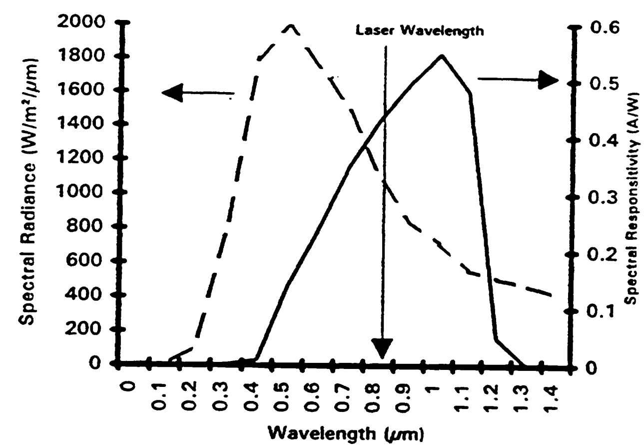

Figure 1: Spectral radiance of the sun and response of typical silicon solar cells

2 SOLAR ILLUMINATION

Geosynchronous satellites use their solar arrays, currently made of silicon, as their primary source of electrical power. The sun's spectral radiance contains energy primarily in the visible and near IR bands as shown by Figure 1.[2] Convolution of the sun's radiant intensity and the silicon solar array responsivity[3] (also shown in Fig. 1) gives approximately 300 A/m^2 of current that the silicon solar cells can produce from the sun's energy. This becomes the definition of "one sun" for the following analyses. Because the laser illumination is single line, a silicon solar cell is more efficient than the aggregate efficiency of collecting sunlight. Thus for the same power, less thermal heating is introduced by the laser.

3 LASER ILLUMINATION

A focused laser system with brightness, B (W/sr), can deliver an intensity, I (W/m^2), at the satellite of

$$I = \frac{B}{R^2} \tag{1}$$

where R is the range from the laser source to the satellite. For a laser system on the surface of the earth at some latitude (L) and a satellite in geosynchronous orbit, R_S = 42,241 km, R_E is the earths radius, and R is

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given by the law of cosines as

$$R = \sqrt{R_s^2 + R_E^2 - 2R_S R_E \cos(L)} \quad (2)$$

For a laser system latitude of 40 degrees (corresponding to the approximate latitude of the Nevada Test Site), $R = 37,579$ km.

At a laser wavelength, $\lambda = 0.865\ \mu$m, the responsitivity of silicon solar arrays is approximately 0.4 A/W. Thus, such a laser system delivers a current,

$$i_L \approx 0.4 I \ \frac{\mathrm{A}}{\mathrm{m}^2} \quad (3)$$

To be equivalent to the sun the laser system must deliver the same current as the sun so the intensity of the laser light at the solar array must be

$$I_1 = \frac{300\ \frac{\mathrm{A}}{\mathrm{m}^2}}{0.4\ \frac{\mathrm{A}}{\mathrm{W}}} = 750\ \frac{\mathrm{W}}{\mathrm{m}^2} \quad (4)$$

Thus, the laser system brightness, B_1, required for the "one sun" condition at geosynchronous orbit is given by

$$\begin{aligned} B_1 &= {}^{\bullet}I_1 R^2 = 750 \frac{\mathrm{W}}{\mathrm{m}^2} \cdot \left(3.7579 \cdot 10^7\right)^2 \mathrm{m}^2 \quad (5) \\ &= 1.06 \cdot 10^{18} \frac{\mathrm{W}}{\mathrm{sr}} \end{aligned}$$

It should be noted here that there is nothing absolute about this "one sun" condition, i.e., with higher brightness than B_1 more electrical current could be delivered by the solar arrays and batteries could be recharged faster than the sun could do it. Obviously, there will be a limit on the amount of intensity that the solar cells can stand without being damaged or degraded by heating effects. Before this limit is reached there may well be a saturation effect where the silicon responsitivity decreases with higher intensity. (It is known that saturation requires at least three "one sun" conditions.) Damage and/or saturation characteristics of solar arrays are details that must be analyzed in conjunction with a laser power beaming concept design. Results of such analysis may well indicate a desirable operating point for a laser power beaming system which is different from the "one sun" condition used as the basic requirement in this analysis.

4 THE BRIGHTNESS EQUATION

An often used approximation for laser system brightness, commonly known as the laser brightness equation, is given by,[4]

$$B = \frac{P\tau}{2\pi\sigma^2} S \ , \quad (6)$$

where,

$$\sigma^2 = \left(\frac{0.45\lambda}{D}\right)^2 + \sigma_j^2 \quad (7)$$

D is the output beam diameter of the laser system, σ_j is the RMS jitter of the output beam, τ is the atmospheric transmission (= 0.85) at a zenith angle of 46.3°.

$$S = \frac{e^{-\left(\frac{2\pi\delta}{\lambda}\right)^2}}{Q^2} \quad (8)$$

where δ is the RMS wavefront error of the output beam and Q is the laser beam quality.

Combining the definitions above into the brightness equation (Equation 6) yields,

$$B = \frac{P\tau e^{-\left(\frac{2\pi\delta}{\lambda}\right)^2}}{2\pi\left[\left(\frac{0.45\lambda}{D}\right)^2 + \sigma_j^2\right] Q^2} \quad (9)$$

This algebraic equation describes the brightness variation as a function of the seven variables previously defined. As already indicated, the "one sun" condition is used in this analysis to set the required brightness for a given laser wavelength and atmospheric transmission coefficient. This leaves five laser system design parameters which can be chosen to meet the laser power beaming brightness requirement: P, D, Q, σ_j and δ.

5 SYSTEM COMPONENTS

Figure 2 describes the major system components for power beaming to space. It includes the high energy laser device with laser power P, the beam control system, the beam director with aperture D, the atmosphere and the satellite. Each of these subsystems have error terms which will contribute the degradation of the overall beam at the satellite. The beam control system is designed to minimize these errors, and to correct for the atmospheric degradation. The system error terms can be expressed in terms of Q, the laser beam quality, which accounts for non-uniform aperture and phase effects out of the laser device itself, σ_j, the residual jitter that the control system is unable to compensate, whether because of accuracy limitations, or because of unmeasured perturbations, and δ, the residual rms wavefront error of the adaptive optics system.

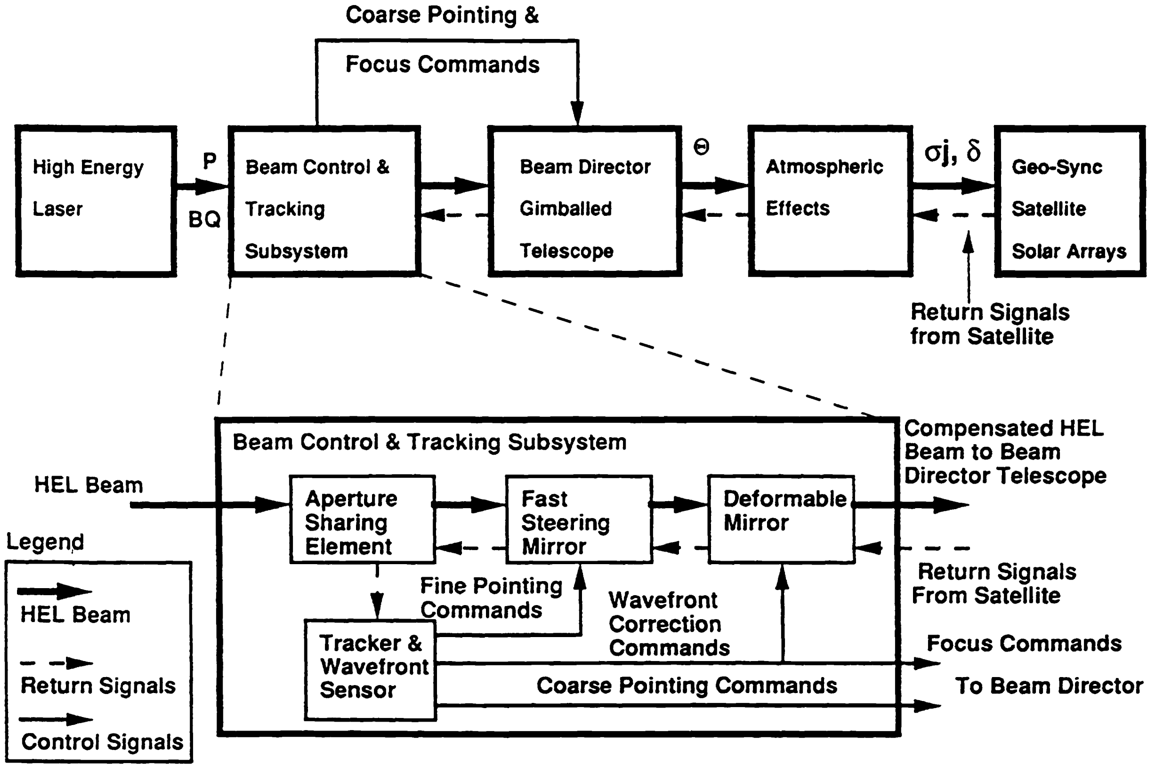

Figure 2: System components block diagram.

These three parameters can be used to make up an overall error budget needed to design the system.

6 SYSTEM PARAMETER TRADE-OFFS

Figure 3 shows the laser power required to achieve the required brightness, B_1, as a function of aperture size (D) and beam jitter (σ_j) for a fixed Strehl ratio of 0.33. This Strehl ratio is typical of what has been achieved with high energy laser systems with the laser power in the megawatt class. Two such systems exist today, both based on chemical laser technology developed originally for missile defense purposes. The high energy lasers in these systems are known as Alpha and MIRACL. Both of these laser systems have adaptive optics correction systems which clean up the laser beam and improve its wavefront error to acceptable levels.

It should be noted that beam jitter induced by atmospheric turbulence naturally varies with atmospheric conditions and experience indicates it will be on the order of 1–3 μrad unless an active correction method using an active jitter sensing scheme and high band-

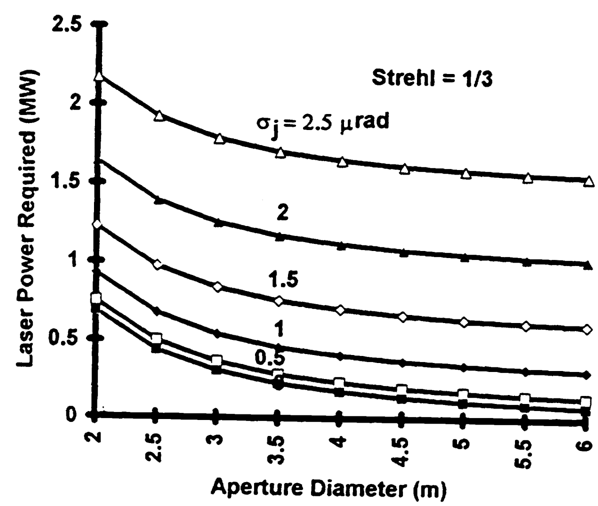

Figure 3: Power required to achieved the "one sun" brightness condition

width beam steering mirrors is successfully employed. The curves in Figure 3 clearly show that laser power of 1–2 MW will be required for a typical aperture size of 4 m unless the jitter can be corrected back to some level less than 0.5 μrad. In this megawatt class power level, non-linear thermal blooming instabilities of the atmosphere can become a serious concern as described in section11. This effect increases the RMS wavefront error and reduces the Strehl ratio. This argues for some combination of lower power and larger output aperture to minimize the effect of exceeding thermal blooming thresholds.

Figure 4 shows the sensitivity of the Strehl ratio to both beam quality and RMS wavefront error. With beam cleanup optics, the Alpha and MIRACL lasers have achieved beam quality in the 1.2 to 2.0 regime so this should be the expected range of beam quality in a reactor pumped laser to be used in a power beaming application. The curves clearly show that achieving a Strehl ratio of 0.33 requires a maximum RMS wavefront error of about 0.08 μm ($\lambda/10.6$) if the beam quality is as poor as 1.5. If $Q = 1.2$ can be achieved, then the wavefront error requirement can be relaxed to about 0.13 μm ($\lambda/6.5$). Clearly, there is a significant trade-off here between the risk of obtaining particular beam quality and wavefront error values for the laser power beaming system.

Another way to look at the trade-offs between system parameters is shown by Figure 5. In this case an aperture diameter of 4 m was chosen based on the fact that several primary mirrors have already been built at or near this size so the risk (and cost) of building a 4 m gimballed telescope for the power beaming system should be acceptable. These curves show the jitter required to achieve the brightness B_1 as a function of laser power and Strehl ratio. Note that for the case where the Strehl is 0.33 and laser power is 1 MW, the required jitter is about 200 nrad. Doubling the laser power to 2 MW allows the jitter requirement to be relaxed to about 350 nrad for the same Strehl. Even with a perfect Strehl of 1.0 the jitter requirement is still about 350 nrad for a power level of 1 MW.

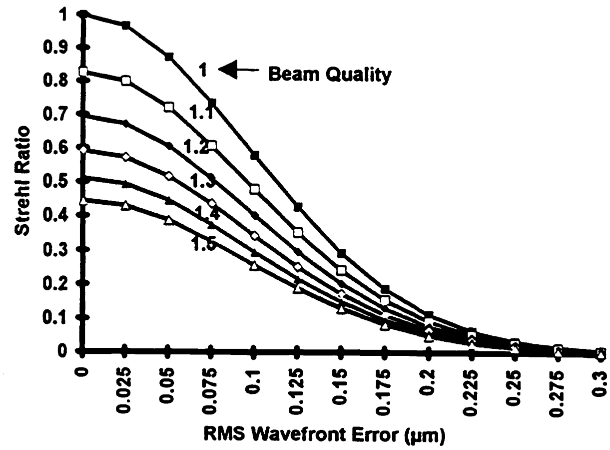

Figure 4: Strehl ratio dependence on wavefront error and beam quality

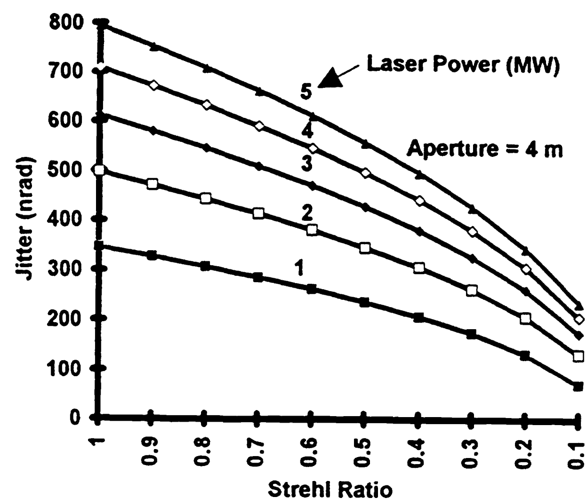

Figure 5: Allowable jitter for various combinations of laser power and strehl ration at a fixed aperture (4m) and beam quality (1.3)

7 THE PARAMETER DESIGN SPACE

Yet another way to examine the system parameter trade-offs is shown by Figure 6. In this case power has been fixed at 5 MW and aperture size at 4 m and the curves show the required jitter as a function of beam

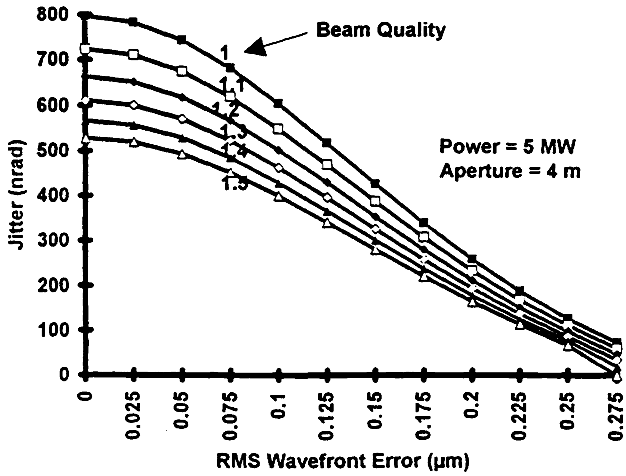

Figure 6: Error budjet for 5 MW laser. Curves represent allowable jitter for a given beam quality and residual wavefront error.

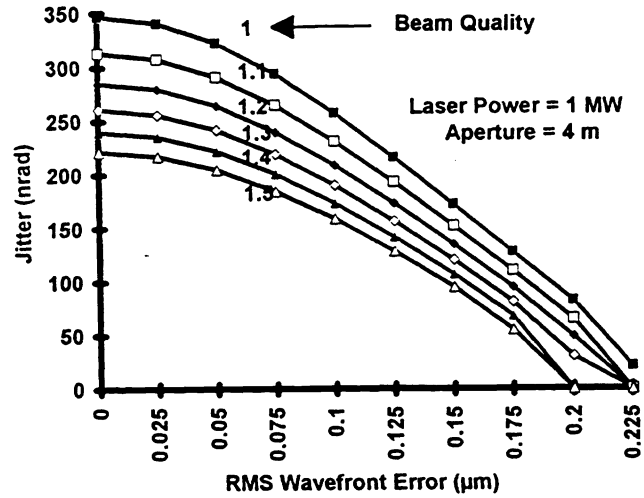

Figure 7: Allowable jitter as a function of various parameters for a 1 MW system.

quality and wavefront error to achieve the brightness B_1. This set of curves show the "design space" available in choosing requirements on jitter, beam quality and wavefront error. Figures 7 and 8 show the effect on the allowable parameter design space as the laser power is reduced from 1 MW to 150 kW. This reduction of laser power shrinks the design space significantly. When the power is 150 kW (Figure 8), the jitter-beam quality-wavefront error design space has shrunk to a very small region indeed. Now even perfect beam quality of 1.0 requires jitter of about 100 nrad and a wavefront error of about 0.05 μm ($\lambda/17$) RMS. When a more realistic beam quality of 1.2 is considered, the jitter requirement becomes about 70 nrad and the wavefront error must be about 0.038 μm ($\lambda/22.4$). These requirements would be extremely difficult to achieve in any practical laser power beaming system.

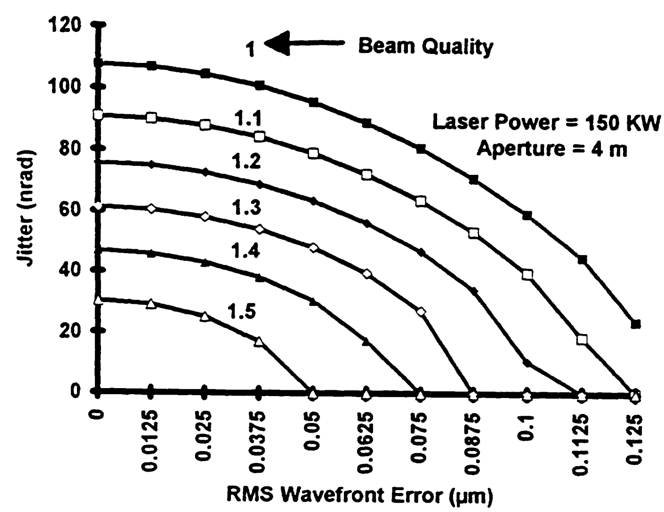

Figure 8: Allowable jitter as a function of various parameters for 150 kW system.

The choice of the laser system parameters to achieve the required brightness is very much a subjective process which depends on the experience and point of view of the one who is making the choice. A person whose expertise is primarily in laser device technology would probably want to keep the power level as low as possible and the beam quality as large as possible. This would tend to minimize the technical risk in eventually achieving these requirements but it would significantly increase the risk of achieving the corresponding jitter and wavefront error requirements. An atmospheric sci-

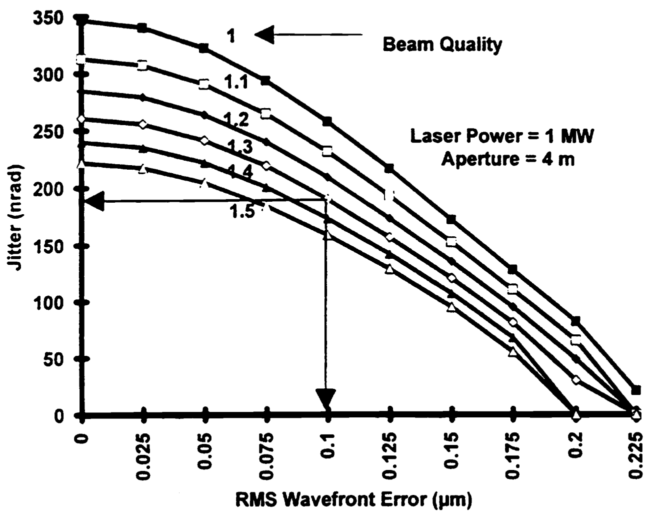

Figure 9: Design point selection based on balancing design risk.

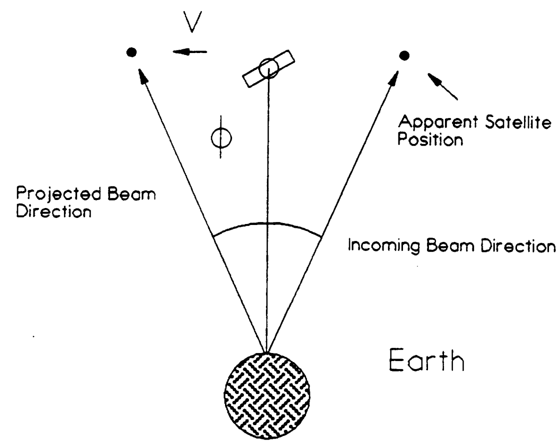

Figure 10: Satellite lead ahead angle for geosynchronous power beaming

entist might want to maximize the allowable jitter since he understands better than anyone else how risky it might be to achieve small beam jitter. An optics specialist might see small RMS wavefront error as the most challenging technology especially when atmospheric effects must be corrected. The only reasonable way to choose a design point with all these conflicts is to use a balanced risk approach where the requirements are chosen so as to leave the technical risk (and perhaps cost) of achieving a particular value balanced among the various parameters.

8 THE SELECTED DESIGN POINT

One choice of laser power beaming system requirements based on a subjective balanced risk approach as described above is shown by Figure 9. The selected system requirements at this design point are as follows:

$$P = 1 \text{ MW}$$

$$D = 4 \text{ m}$$

$$Q = 1.3$$

$$\sigma_j = 200 \text{ nrad}$$

$$\delta = 0.1\ \mu\text{m}\ (\lambda/8.5)$$

These requirements can serve as a starting point to guide the designers of a laser power beaming system based on reactor pumped or other high power laser technology.

9 LEAD ANGLE AND ATMOSPHERIC ISOPLANATIC ANGLE

The satellite always appears in a fixed position in the sky (Figure 10). The actual position of the satellite, however, lies in front of the observed position. (This is analogous to the actual position of an aircraft being ahead of the position indicated by its noise.) The angle between the actual satellite position and its apparent position is given by ϕ:

$$\phi = \frac{v}{c} \quad , \tag{10}$$

where v is the GEO satellite velocity and c is the speed of light. Using the appropriate numbers ($v = 2.67$ km per second and $c = 300,000$ km per second) this equation gives $\phi = 9.0 \times 10^{-6}$ radians (i.e., 1.85 arcsec). Whereas a return signal appears to originate behind the actual satellite position, the outgoing power beam must be aimed ahead of the satellite by the same angle, ϕ. Thus the angular difference between the incoming tracking signal and the outgoing beam is 2ϕ (i.e., 18 μrad). If the adaptive optics is to work efficiently, the atmospheric isoplanatic angle, θ_o, must be greater than this angle (unless laser beacons are used). Thus,

$$\theta_o > 2\phi \quad . \tag{11}$$

At 2.2 km (7,200 feet) altitude and at visible wavelengths, the isoplanatic angle typically lies between 2 and 4 arcsec (9.7–19.5 μrad).[5] At longer wavelengths, the isoplanatic angle, θ_o, increases with wavelength as follows[5]:

$$\theta_o \sim \lambda^{\frac{6}{5}} \quad . \tag{12}$$

Thus, at wavelength 0.865 μm, the isoplanatic angle at 2.2 km altitude lies in the range 3.4 – 7 arcsec (16.5 - 33.9 μrad). For GEO satellites, isoplanatic angles in this range just satisfy expression 11. Sea level sites would probably not be suitable for our application except in good seeing conditions.

Atmospheric isoplanatic angle is not affected by turbulence near the ground. Turbulence at high altitudes has a more dominant effect. Since the jet stream is at high altitude (35,000 feet) and strong turbulence is often associated with it, suitable sites for the system might be at latitudes (such as the tropics) which are rarely affected by the jet stream.

10 ADAPTIVE OPTICS

10.1 Adaptive segment size

In 1 arcsec (4.8 μrad) seeing in visible light ($\lambda =$ 0.55 μm), the Fried parameter, r_o, is $\sim$ 0.1 m. At other wavelengths, r_o increases with wavelength as follows:

$$r_o \sim \lambda^{\frac{6}{5}} \tag{13}$$

It follows from this expression that, in the same seeing conditions, at the longer wavelength 0.865 μm, $r_o =$ 0.17 m. Thus for these seeing conditions, an adaptive segment size of about 0.15 m is suitable for correcting atmospheric turbulence. With a 4-meter telescope, about 1000 such segments would be required to cover the whole aperture.

10.2 Maximum piston

The overall RMS wavefront error introduced by atmospheric turbulence over the whole telescope diameter (before the adaptive optics are operated), σ_o, is given by[6]

$$\sigma_o = (1.0299(\frac{D}{r_o})^{\frac{5}{3}})^{\frac{1}{2}}\frac{\lambda}{2\pi} \quad , \tag{14}$$

where D is the telescope diameter. For $D = 4$ m in poor seeing where $r_o = 0.05$ m at 0.55 μm, the RMS error $\sigma_o = 3.42$ μm. The peak-to valley (P-V) wavefront error; is about $\times 3$ larger than the RMS error. Thus in poor seeing conditions the adaptive segments would have to piston over $\sim$ 12 μm range.

The piston requirement can be significantly reduced if tip/tilt corrections are carried out separately using a tip/tilt mirror because a significant portion of the turbulence energy is in the tip/tilt Zernike modes. By use of such a mirror, the residual piston requirement of the adaptive optics reduces to $\sim$ 2 μm. When thermal blooming is taken into account (Section 10) the 2 μm piston requirement just derived is found to increase significantly. The tip/tilt mirror can also be used to compensate telescope shake which in many instances is a more significant contributor to wavefront tip/tilt than atmospheric turbulence.

10.3 Residual wavefront errors and Strehl intensity

If each segment is adjusted for piston and tilt, the residual RMS wavefront error over the segment, σ_s, is given by

$$\sigma_s = (0.134(\frac{a}{r_o})^{\frac{5}{3}})^{\frac{1}{2}}\frac{\lambda}{2\pi} \quad , \tag{15}$$

where a is the segment dimension (diameter). For $r_o =$ 0.1m and $a = 0.15$m, this equation gives the residual error $\sigma_s = 0.045$ μm. In 2 arcsec ($\sim$ 10 μrad) seeing at 0.55 μm ($r_o = 0.05$ m) the residual error $\sigma_s = 0.08$ μm. If the adaptive optics works perfectly otherwise, the residual RMS wavefront error over the entire telescope aperture is given by equation 15. In poor seeing conditions ($r_o = 0.05$ m and $\sigma_s = 0.08$ μm) the Strehl intensity pull-down due to the 0.15 m segment size is 0.71. Of course, other factors (such as atmospheric isoplanatic angle, system noise etc.) reduce the overall Strehl intensity of the complete adaptive optic system to a lower value.

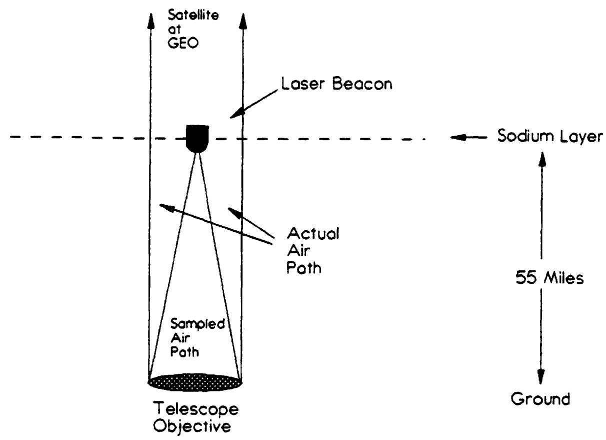

Figure 11: Focal anisoplanatism is a measure of how well the laser beacon samples the true air path to the satellite

10.4 Laser beacons and other reference sources

A bright, and preferably, point object is needed as a reference for the adaptive optics. There are three possibilities: (1) bright nearby stars, (2) laser beacons, and (3) power beam reflections/glints from the satellite. Because the satellite moves continuously against the background stars and because suitably bright stars cannot generally be found within the isoplanatic patch, stars are not suitable as the adaptive optics reference. Laser beacons are a possible alternative but significant development in laser beacon technology is required before this technology can be utilized. As shown in Figure 11 the problem of focal anisoplanatism makes it necessary to have multiple beacons to correct the wavefront over large telescope apertures. Over a 4-meter aperture, six beacons might be necessary. The stitching together of the six corrected wave portions to form a single coherent corrected wavefront has not been demonstrated at the present time. The other equally fundamental problem associated with laser beacons is the problem of correcting overall wavefront tip/tilt. This problem arises because the laser beacon light has to first propagate through the atmosphere to the reflective layers in the atmosphere (perhaps the sodium layer at an altitude of 90 km or possibly lower altitude regions where reflections are obtained from O_2 and H_2 molecules). Conventional theory indicates that the RMS angular jitter, σ_θ, of a beam which has propagated up through the atmosphere is given by[6]

$$\sigma_\theta = \frac{\sqrt{2}}{\pi}\frac{\lambda}{D}\sqrt{0.8959(\frac{D}{r_o})^{\frac{5}{3}}} \qquad (16)$$

For $D = 4$ m, $r_o = 0.17$ m and $\lambda = 0.865$ μm, the angular jitter is about 1.28 μrad. At 37,500 km altitude, this gives rise to a RMS spot jitter of 48 meters which is unacceptably large — enough to reduce the overall delivery efficiency of the system by a factor ~ 10. Even if there is evidence[7,8] that suggests that the jitter predictions of conventional theory are pessimistic, additional jitter contributions arising from microseismic ground motion and telescope shake could make the overall jitter amount even larger than that given by the above equation. To correct beacon jitter, a stable reference object is needed. As has already been stated, stars are not suitable because there are not enough bright stars lying within the isoplanatic patch. A more practicable option is to use a return signal from the satellite itself. We now look at this option.

10.5 Return signal from the satellite and noise

Let us assume that the laser beam power is 1 MW and that the fraction 0.03 is Lambertianly reflected from the satellite. (This fraction includes both satellite reflectivity and other losses.) Thus 30,000 W are returned from the satellite. The power collected by the telescope, C, is given by

$$C = 5.5 \times 10^{-12} D^2 \quad , \qquad (17)$$

where D is expressed in meters and C is expressed in Watts. The number of photons arising per second, N, is given in terms of C by

$$N = \frac{C}{h\nu} \quad , \qquad (18)$$

where $h = 6.6 \times 10^{-34}$ is Planks constant and $\nu = 3.46 \times 10^{14}$ Hz is the light frequency. For a 4-meter telescope, $C = 8.8 \times 10^{-11}$ W, and $N = 4.0 \times 10^9$ photons. An average of 4.0×10^6 photons per second fall on each of the 1000 adaptive segments. To reliably compensate atmospheric turbulence, the system time constant must be about 1 msec, i.e., about $\times 10$ shorter than the atmospheric turbulence time constant. If a Shack/Hartman lenslet array is used, the maximum number of photons falling on each adaptive segment in each 1 msec time period is 4000. The actual number utilized, however, could be only about 700 if temporal beam-sharing is used with a $\frac{1}{6}$ time fraction being allotted to the return signal. For each adaptive segment, the fundamental RMS tip/tilt error due to shot noise, E_t, is given in radians by

$$E_t \approx \frac{\lambda}{a\sqrt{N_s}} \quad , \tag{19}$$

where a is the segment dimension and N_s is the number of photons utilized with each segment. The effective RMS wavefront error, σ_w, due to this tip/tilt error is given by

$$\sigma_w = \frac{\lambda}{\sqrt{8N_s}} \quad . \tag{20}$$

If we assume that $\frac{1}{6}$ of the photons can be utilized, i.e., $N_s = 700$ and $a = 0.15$ m, the RMS angular error is about 2.0×10^{-7} radians, and the corresponding RMS wavefront error is $\sim$ 0.01 μm. These RMS errors are unavoidable but are acceptably small. Other noise sources, however, are present, e.g., thermal noise in the detector. Effort would be needed to reduce these to acceptable levels. Thermal noise could of course be reduced by simply cooling the detector.

If the scatter from the P-V cell is specular rather than Lambertian, much smaller return signals could arise than those just indicated. Since the P-V cell would not generally be oriented exactly perpendicularly to the incoming beam, for much of the time the return signal would be too small to be useful. In these circumstances, it would be necessary to fix corner cube reflectors to the satellite.

10.6 Corner cube reflectors

If a corner cube reflector is used, the return signal can be increased by several orders of magnitude compared to the signal arising from a Lambertian reflector. Assuming that the corner cube is almost perfectly reflecting and has diameter d, the signal power collected by the telescope is given in Watts by

$$C = \frac{P\,d^4 D^4}{1.5 \times 10^{31} \lambda^4} \quad , \tag{21}$$

where d, D and λ are all expressed in meters and again P is the laser beam power in Watts. For P=1 MW, $d = 0.0$ m and $D = 4$ m, $C = 3.0 \times 10^{-7}$ W. Thus even a small (1 cm diameter) corner cube produces a large increase in return signal compared to Lambertian scattering from the P-V cell.

11 THERMAL BLOOMING

Because the satellite lies at a fixed point in the sky, in zero-wind conditions the laser beam always propagates through the same column of air. Because there is no beam slewing to distribute the heat, the air column becomes hotter and hotter until eventually convection currents develop which do cause air movement in the column. We do not model this very complex case here. Instead we consider the simpler case of a steady wind throughout the height of the atmosphere with velocity V ($V \neq 0$). In these conditions the air mass in the beam propagation column is refreshed in a time period given by $D/(V\cos\alpha)$, where α is the satellite zenith angle and again D is the telescope diameter. The maximum increase in temperature of the air, δt, as it emerges from the propagation column is given by

$$\delta t \approx 3.0 \times 10^{-8} \frac{P\,(1 - \tau(h)^{sec(\alpha)})}{S\,V\,D\,\exp(\frac{-h}{8350})} \,\text{degs C}, \tag{22}$$

where the conversion factor 4.18 Joules per calorie has been used, P is the laser beam power, S is the specific heat of air compared to water, h meters is the altitude of the site, and $\tau(h)$ is the atmospheric transmission over a vertical propagation path starting at altitude h. (It is noted that the pessimistic assumption is made in this equation that all light which is not transmitted by the atmosphere is absorbed in the form of heat. The result is that the equation yields worst case temperature rises.) The quantity $\exp(-h/8350)$ is the fractional mass of air above altitude h. For $D = 4$m, P=1 MW, $\alpha = 45$deg, $h = 2200$m, $S = 0.25$ (specific heat of water =1), $V =$ 5m per sec ($\sim$ 10 mph), and $T(2200) = 0.9$, the increase in temperature $\delta t = 1.0 \times 10^{-3}$ degs C. The reduction in optical path distance, OPD, caused by this temperature increase is given in meters by

$$OPD = \frac{\delta t(n-1)}{t\,\sin(\alpha)} \int_h^\infty e^{\frac{-h}{8350}} dh \,, \tag{23}$$

where n is the refractive index of air at sea level and t is the surrounding air temperature in degrees Kelvin. Equations 22 and 23 combine to give

$$OPD = 3.0 \times 10^{-8} \frac{P\,(1 - \tau(h)^{sec(\alpha)})\,(n-1)}{V\,S\,D t\,\sin(\alpha)\,\exp(\frac{-h}{8350})} \times \int_h^\infty e^{\frac{-h}{8350}} dh \quad \text{meter.} \tag{24}$$

If the OPD numbers from this equation are less than the maximum piston error caused by atmospheric turbulence, an adaptive optics scheme that corrects for atmospheric turbulence will also correct for thermal blooming. In poor night seeing conditions, the maximum piston error for a 4-meter telescope is of the order $12\mu m$ (see Section 10.2). The thermal blooming OPD errors are likely to be less than this amount if the laser site is at high altitude. If the site is at sea level and/or the wind velocity is small, the thermal blooming OPD errors could exceed this amount.

11.1 Example of OPD changes due to thermal blooming

If the laser is projected at $\alpha = 45$ deg from a site at altitude $h = 2200$m and the following choice is made for the other parameters: $t = 293$ deg K, $D = 4$ m, $V = 5$m per sec, $\tau(2200) = 0.9$, $P = 1$ MW, $n = 1.0003$, and $S = 0.25$, the optical path length change $OPD = 10\ \mu$m. For this worst case estimate, this path change is comparable to the path changes caused by atmospheric turbulence (Section 4.2), and thermal blooming is a significant problem.

12 SUMMARY AND CONCLUSIONS

A specification has been established for a system which beams laser power to geosynchronous satellites using reactor pumped laser technology. Although only a few kW of power are finally delivered to the satellite, a 1 MW laser beam is required initially because of beam losses arising from sources such as laser beam jitter, thermal blooming, atmospheric turbulence and atmospheric isoplanatic angle.

The specification, which is obtained from a subjective balanced risk approach, calls for the laser beam to be projected through a 4-meter diameter telescope. The telescope must be sited at a high altitude site where overflight is restricted. At the Nevada Test site altitudes ~ 7000 ft are possible. Even at high altitudes, adaptive optics is still needed to overcome the effects of atmospheric turbulence, thermal blooming and laser beam jitter.

The adaptive optics requirement is for about 1000 adaptive optics segments over the 4-meter telescope aperture, all operating at about 1000 Hz. The most recent adaptive optics demonstrations, however, correct over significantly smaller apertures (1.5 m) and hence some development in adaptive optics technology is required.

The adaptive optics reference can be either a laser beacon or a return signal from the satellite itself. If laser beacons are used, atmospheric isoplanatic angle ceases to be an issue. However, three other problems remain which cause reduced system efficiency: (1) Thermal blooming causes degradations to the laser beacon spot (in addition to those caused by atmospheric turbulence). These will reduce the accuracy of the adaptive optic correction from levels so far demonstrated. (2) The problem of focal anisoplanatism over a 4-meter aperture necessitates multiple laser beacons. Implementation of multiple beacons has still to be demonstrated. (3) Since tip/tilt cannot be corrected using the beacon, there still remains the requirement for a suitably bright reference signal from the satellite itself to make this correction.

If all of the adaptive optics correction is made using a reference signal from the satellite and no use is made of laser beacons, other problems have to be overcome: (1) The 18 μr lead angle requirement makes it necessary to site the system at high altitudes ($>$ 7000 ft) where the atmospheric isoplanatic angle is suitably large. (2) To obtain a suitably strong return signal from the satellite, it is necessary to use a reflection of the (MW) power beam itself. This necessitates aperture sharing.

Because of problems associated with reference signals from the satellite discussed in Section 9.5, it would be desirable to equip future satellites with corner cube reflectors or other similar devices. Even a 1 cm^2 corner cube dramatically increases return signal strength.

The system requirements indicated in the paper are easily adapted as the various contributing technologies mature. Clearly the system size is a very strong function of the ability to correct for degradations caused by the atmosphere and other sources. With significant advances in the technologies, a reduction of a factor of five in the laser system size may be possible. In this paper, we have judged it easier to build a more powerful laser than to assume that extremely high performance correction can be readily achieved.

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