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ADAPTIVE OPTICS FOR LASER POWER BEAMING

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It has been proposed to use a high energy pulsed laser to beam power into space for satellites or a lunar base. The effects of atmospheric transmission are critical to such a system. Thermal blooming in the atmosphere can cause the beam to spread rapidly. Atmospheric turbulence can cause beam bending or beam spreading, resulting in the loss of transmitted energy that fails to hit the target receiver.

If the laser beam is expanded to a width of 12 m using a Cassegrain beam expander, and the beam is collimated, thermal blooming will be minimized. An adaptive optics system has been proposed to compensate for the effects of turbulence. The primary mirror is made up of hexagonal segments which can each be moved in a piston or two axis tilt manner. A Hartmann Shack sensor is used to measure the wavefront of radiation from a distant source, called a beacon. In our case, the beacon is a ''spot'' formed by the reflection of a laser beam by atmospheric aerosols, referred to as an artificial guide star. A laser pulse is transmitted into the atmosphere, and the wavefront of the radiation reflected by aerosols at a desired altitude is measured and used to impose a wavefront correction on the shape of the primary mirror. The next laser pulse is transmitted with this correction, which compensates for the effects of turbulence. The system is shown in Figure 1 below.

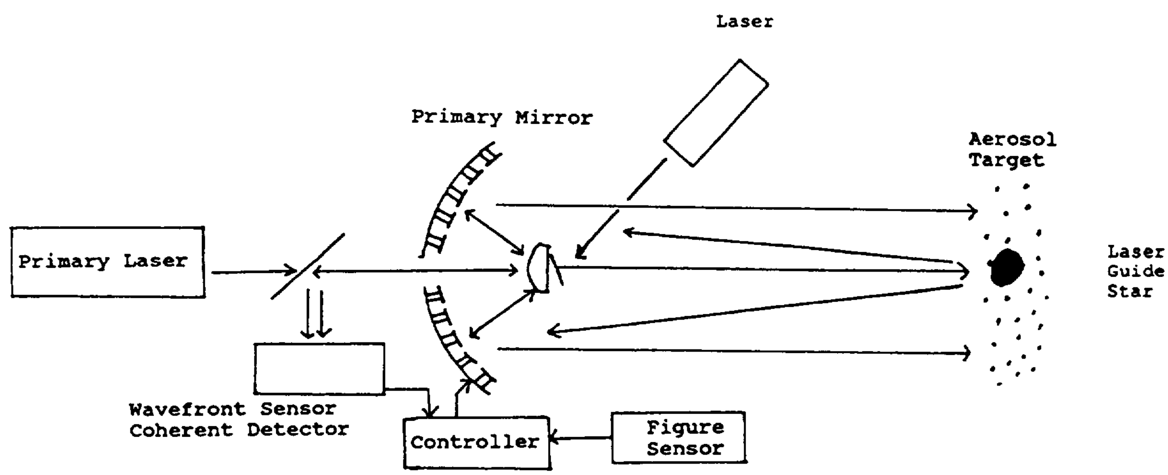

Figure 1.

The goal of the adaptive optics system is to obtain a diffraction limited 12 meter collimated beam at a given altitude. We consider three schemes for creating beacons using artificial guide stars, and the resulting system performance.

Case 1. Entire 12 m Beam Used as Guide Star.

Suppose the reflection from the 12 meter beam itself is used as a beacon. This idea is attractive, since we will be getting a return signal from all points of the 12 m beam at the chosen altitude. However the beacon occupies an area larger than the isoplanatic patch. To calculate the isoplanatic patch, we assume the mean turbulence profile of the Hufnagel-Valley-Boundary model:

$$C_h^2(h) = .374*(2.2E-53\ h^{10} \exp(-h/1000) + 1.E-16 \exp(-h/1500) + 1.7E-14 \exp(-h/100))\ m^{-2/3}$$

This turbulence profile corresponds to a value of the Fried coherence length of r0 = 23 cm for a 1μ wavelength, which would be 10 cm for visible light. The isoplanatic angle $\theta_{I\rho}$ and isoplanatic patch $D_{I\rho}$ are shown in Table 1 for several guide star altitudes.

Altitude km	$\theta_{I\rho}$ arc sec	$D_{I\rho}$ m
7	29.3	1.99
12	12.2	1.42
30	8.2	2.38
60	8.2	4.76
90	8.2	7.13

Table 1. Isoplanatic angle $\theta_{I\rho}$ and patch diameter $D_{I\rho}$

The data in Figure 2 assumes the laser is pointed vertically, and that there is no significant turbulence layer at tropopause (about 12 - 15 km). A significant turbulence layer at tropopause would greatly reduce the isoplanatic angle for guide stars above 15 km, as would deflection of the beam from vertical. At 90 km the guide star is assumed to be formed by exciting the sodium layer. At 60 km the concentration of aerosols is extremely low.

Since the beam diameter is larger than the isoplanatic patch, we cannot use the return from the entire beam for wavefront correction. Since the Hartmann wavefront sensor will use coherent detection, the signal to noise ratio in the wavefront measurement will be decreased due to speckle from the 12 m beacon. Hence use of the entire 12 m beam for wavefront correction appears infeasible.

Case 2. Single Guide Star with Small Radius.

An alternative approach is to produce a smaller guide star with a second laser. This avoids the problems of signal loss due to speckle. Anisoplanatism is still a problem, however, since the primary mirror aperture is larger than the isoplanatic patch at any of the altitudes under consideration. Hence a single guide star cannot be used to correct the effects of turbulence over a 12 m aperture.

Case 3. Multiple Guide Stars.

For ground based large aperture telescopes it has been proposed to use multiple guide stars, and to correct the wavefront on the subaperture of the mirror directly below a guide star based on the return from that star. In this manner, the effects of anisoplanatism are greatly reduced. This technique could be used for the laser power beaming problem. Each guide star would be used to correct the part of the beam expander mirror within an area that is a fraction of the the isoplanatic patch around the guide star. In this way the part of the beam in the isoplanatic patch around the guide star will be corrected for turbulence effects, relative to the position of the guide star. The number of guide stars needed depends on the diameter of the primary mirror aperture and the size of the isoplanatic patch. For wavefront correction with rms error of $\lambda/10$, it is required that

$$Ngs = (1.25\ D/D_{IP})^2$$

where Ngs is the number of guide stars, and D is the mirror aperture, 12 m in this case. The number of guide stars required at several altitudes is given in Table 2 below.

Altitude km	Number of Guide Stars (Ngs)
7	57
12	112
30	40
60	10
90	5

Table 2. Multiple Guide Star Requirements

Power Considerations:

Each guide star at a given altitude requires sufficient brightness, or laser power, in order to provide enough photons for each cell of the Hartmann sensor to produce a wavefront slope measurement. If the guide stars are created at higher altitudes, we require more power per star, since the density of aerosols is lower, however we need fewer stars. Hence the amount of power needed to produce 57 guide stars at 7 km is less than that needed to produce 40 guide stars at 30 km. However, guide stars at 30 km could be used to correct for turbulence at tropopause, whereas wavefront correction based on a star at 7 km would be limited to turbulence in the boundary layer and a few kilometers above. Since the most intense turbulence is in the boundary layer, a guide star at 7 km may yield good performance. In addition, it is easier to precisely position the guide stars at the lower altitude, since the angular separation between them is greater.

Referencing and Positioning of Multiple Guide Stars

Since our beacon is in the atmosphere, and not on the target, no correction can be made for pointing errors, or overall tilt of the wavefront. When using multiple guide stars, the average tilt of the wavefront over the subaperture around each guide star cannot be corrected. If the guide stars are positioned correctly with respect to each other, this does not present a problem. However if the guide stars spread out, then the corrected beam will also spread. Hence it is required that the guide stars be positioned accurately with respect to each other. In an experiment on Mt. Haleakala, Maui, Hawaii [2], two guide stars were produced about 30 cm apart at an altitude of 6 km. A second telescope was used to verify the position of two guide stars.

Production and Sensing of Multiple Guide Stars

In the Mt. Haleakala experiment, the guide stars were produced by two staggered pulsed lasers, and a switching tip-tilt mirror. In this manner, by gating the returns from the guide stars, the returns from each star could be separated and associated with the corresponding primary mirror subaperture. This approach is not practical for larger numbers of guide stars, since the delay time between sensing the wavefront and transmitting the corrected laser pulse must be less than about 10 ms. In the multidither approach the wavelength of each guide star is shifted about $\lambda/15$ so that each star has its own frequency, and can be discriminated using coherent detection. A third approach is to produce an array of guide stars, and use appropriate stopping and vignetting in the optical path so that each cell in the Hartmann sensor sees a single guide star through an appropriate subaperture of the primary mirror. The wavefront sensor would be located behind the primary mirror in the optical path and a beam splitter would be required in the path of the primary laser. Wavefront sensors could not be integrated into the primary mirror segments, as is currently being discussed. The multidither approach would allow the wavefront sensors to be integrated into the mirror segments.

Conclusions

Turbulence compensation for a 12 m laser beam will require multiple guide stars produced by a second laser. The number of guide stars required at various altitudes was calculated. The potential costs and benefits of using low or high altitude guide stars were discussed in terms of power requirements, positioning and wavefront correction.

References

1. Gardner, C.S., Welsh, B.M., ''Design and Performance Analysis of Adaptive Optical Telescopes Using Laser Guide Stars'', IEEE Procedings, Vol. 78, No. 11, Nov. 1990.

2. Murphy, D., Primmerman, C., Zollars, B., Barclay, H., '' Experimental Demonstration of Atmospheric Compensation Using Multiple Synthetic Beacons'', submitted for publication.