Astronomers are building giant telescopes to explore the far reaches of the universe. The Keck telescope, with its 10 m segmented primary mirror, is the largest in the world. Nearly a dozen 8 m class telescopes with monolithic primary mirrors are either under construction or in design. These giant light collectors will enable astronomers to detect the faintest objects in the sky. But the random, inhomogeneous motion of the atmosphere robs them of a clear view. The angular resolution of an 8-10 m telescope looking through the Earth's atmosphere is no better than that of an 8-10 inch telescope.

The future exploration and exploitation of space will depend on propagation of laser beams through the Earth's atmosphere. Fiber optics and photonics have revolutionized the communication industry. In a similar way, laser beam communication with scientific probes in deep space (even beyond the solar system) will increase information bandwidth and reliability while reducing weight, antenna size, and power consumption. Lasers can also be used to beam power to geosynchronous satellites, space stations, and even to scientific outposts on the moon. But once again, the turbulent atmosphere is a problem. Atmospheric turbulence causes laser beams to spread out. The atmosphere destroys the advantage afforded by large aperture telescopes to keep the beam concentrated over long distances.

In imaging and laser beam transmission applications, diffraction sets the limiting angular resolution or the angular divergence of a laser beam. For a wavelength $\lambda$ and telescope diameter $D$, the diffraction limited angular resolution is roughly $\lambda/D$. However, the atmosphere effectively limits $D$ to a value of 10-20 cm. Let's try to understand this in a bit more detail.

**Atmospheric Wavefront Distortion**

The atmosphere is a randomly inhomogeneous medium in turbulent motion. It is a swirling fluid whose temperature and velocity vary randomly. The most significant effect on the propagation of light is the variation of the air's temperature. The refractive index of air decreases approximately 1 part in $10^5$ for every degree Kelvin increase in temperature. Since the speed of light is inversely proportional to the refractive index, light waves passing through a medium of varying refractive index become distorted. Some parts of the wavefront are slowed more than others. A large surface of constant phase is transformed into many small regions traveling in randomly varying directions.

If we use a large aperture telescope to focus the distorted wavefront onto a camera at the telescope's focal plane, we get a blurred image much larger than the diffraction limit of the aperture, $\lambda/D$. Light from different spatial regions ends up at different parts of the focal plane. If we make the telescope aperture smaller and smaller, we eventually reach a size where the instantaneous image (as would be obtained by a very short exposure) is limited by diffraction at the aperture. The image will still be moving around in the focal plane, but it will have a diffraction limited intensity profile. That is, there is some limiting aperture size over which the phasefront is essentially a tilting plane wave.

The aperture size through which we can form a diffraction limited image was originally defined by Fried as the coherence diameter of the atmosphere, and is universally designated as $r_0$. At a given location on the Earth, $r_0$ may vary from 5-30 cm (for zenith viewing at 0.5 μm wavelength). The average value of $r_0$ varies significantly from site to site but can be of the order of 15-20 cm at the best mountaintop astronomical observatories. $r_0$ depends on the height distribution of the strength of turbulence. It is a function of wavelength and angle of viewing through the atmosphere. In the infrared, where the absolute value of the wavefront distortion is a smaller fraction of the wavelength, $r_0$ is larger. It increases as $\lambda^{6/5}$. As we observe through more atmosphere (at lower elevation angles), $r_0$ decreases— as the $3/5$ power of the cosine of the zenith angle. At 30° elevation ($60°$ zenith), $r_0$ is 66% of its value looking directly overhead.
Adaptive Optics Concept
Adaptive optics is a concept for correcting wavefront distortions in real time. The idea was proposed by the astronomer Horace Babcock in 1953. In simplified terms, the objective of adaptive optics is to get all parts of a wavefront traveling in the same direction. This is done by sensing the tilt over many small regions of the wavefront and adjusting a deformable, or “rubber,” mirror to remove those tilts. We must continually update the surface figure on the deformable mirror to keep up with changes in the atmosphere. To use an old expression, this is easier said than done. It was nearly 20 years after Babcock’s paper before the first deformable mirror experiments were done in atmospheric turbulence on real telescopes.

The essential components of an adaptive optics system are a beacon, the deformable mirror, a wavefront sensor, and processing and control electronics. The beacon, located near the object of interest, emits waves of light that travel through the turbulent path to be compensated. The light from the beacon is collected by the telescope’s aperture and reimaged onto the deformable mirror. After reflection from the deformable mirror, the compensated wavefront is analyzed by the wavefront sensor for residual error. The residual error signals are filtered, amplified, and applied to the actuators of the deformable mirror to close the adaptive optics loop.

Need for Laser Beacons
Applications of adaptive optics to astronomy and laser beam propagation into space are difficult because, in most cases, a sufficiently bright natural beacon is not nearby, or does not exist at all. For astronomy, a natural star beacon must be as bright as 6th to 12th magnitude, depending on the imaging wavelength (visible or infrared) and seeing conditions. Fainter stars can be used if poorer correction is adequate. Individual choices and tradeoffs of system complexity vs. performance must be made. In some applications, such as power beaming to geosynchronous satellites eclipsed by the Earth’s shadow, a beacon does not exist at all.

Adaptive optics beacons can be created at any position in the sky by pointing a focused laser beam in the atmosphere and observing the backscattered light. This concept has been under investigation for more than a decade in a classified U.S. Department of Defense program. The technical details of the program were declassified in 1991. The laser beacon concept was independently reported by astronomers in France in 1985. Two scattering mechanisms are practical—Rayleigh scattering from air molecules in the stratosphere (beacon ranges of 10-20 km) and resonant fluorescence scattering from atomic sodium in the mesosphere (80-100 km). It is convenient to use a pulsed laser to create the beacon so that the wavefront sensor can be “range-gated” to exclude light scattered from all ranges except where
the beam is focused in the atmosphere. Typical range-gate lengths are 1-2 km for Rayleigh scattering beacons and 10-15 km for sodium layer beacons.

Figure 1 shows the essential elements of a laser beacon adaptive optics system for astronomical imaging. A laser beam transmission system would be similar. The laser is pointed at the object being imaged. In this example, the laser shares the telescope aperture via a high performance laser line reflection filter. A polarizing beam splitter and quarter-wave plate form a duplexer, sending the outgoing light to the telescope, but allowing the backscattered light to pass through the beamsplitter to the wavefront sensor. Appropriate optics register an image of the deformable mirror on the entrance pupil of the wavefront sensor to fix the relationship between the subapertures in the wavefront sensor and the actuators in the deformable mirror. Light at all wavelengths, other than the laser beacon wavelength, is transmitted through the filter and divided between the guide star tracker and the scientific camera (or other instrument).

**Laser Beacon Limitations**

At this point it is important to describe two significant limitations of laser beacons for adaptive optics. First, laser beacons cannot be used to sense the tilt component of atmospheric wavefront distortion. Second, using a laser beacon introduces a sensing error caused by the finite altitude of the beacon.

Why can’t we use the laser beacon for tracking? Why doesn’t it provide information about atmospheric tilt? As the laser beam propagates up from the Earth through the atmosphere, it is steered randomly by the turbulence. The focused spot ends up laterally displaced—a random, unknown amount from the optical axis of the telescope. Basically, we do not know where the beacon is with respect to an inertial reference frame (like the fixed stars). We cannot, therefore, use it to measure atmospheric tilt. If the laser shares the full aperture of the imaging telescope, the backscattered light returns to the telescope down the same atmospheric path arriving at the telescope’s aperture on axis—just as it left. Consequently, the full aperture image of the laser beacon always appears to be centered in the focal plane (because of reciprocity), while the image of a star dances about the focal plane due to its one way passage through the turbulence.

How significant is the loss of tilt information? Noll analyzed the spatial distortions due to turbulence in terms of Zernike polynomials—decomposing the aberrations into common terms such as X and Y tilt, defocus, astigmatism, coma, spherical aberration, and all the higher-order terms. His analysis shows that, when atmospheric distortions are expressed as mean square phase, 87% of the power is tilt. All higher-order distortions account for only 13% of the power.

The highest priority of any adaptive optics system should be correction of full aperture tilt. Even if the higher-order compensation is perfect, a long exposure image would be smeared out so badly it would be difficult to recognize that adaptive optics was being used. We must therefore find a means to do tilt correction. Fortunately, we have several factors in our favor when sensing full aperture tilt compared with sensing higher-order distortions: (1) we can use the entire aperture, (2) the image of the natural star will be compensated, making a nearly diffraction limited image on the track sensor, (3) in theory we need only four discrete detectors and can use high quantum efficiency photon counters, and (4) it has been shown that the required sampling time for tilt sensing can be significantly longer than higher-order sensing. These factors taken together allow the use of natural stars fainter than 20th magnitude for sensing full aperture tilt, providing essentially 100% sky coverage. Astronomers working at the Canada-France-Hawaii Tele-

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**Figure 1.** Essential components of a laser beacon adaptive optics system. In this configuration, the beacon laser shares the full aperture of the telescope by means of a narrow band laser line filter. A polarizing beam splitter and quarter-wave plate form a duplexer, allowing the backscattered light to pass through the beam splitter to the wavefront sensor. A separate tilt sensor tracks a natural guide star near the science object using the full aperture of the telescope. The secondary mirror of the telescope serves as the fast steering mirror to correct full aperture tilt.
scope have already demonstrated high performance tracking with the HRCam system on 19th magnitude stars.\textsuperscript{13}

**Higher-Order Compensation with Laser Beacons**

Given that the laser beacon can only be used to compensate for higher-order distortions, how well does it work? The beacon's finite altitude creates two effects not present with natural beacons. First, we cannot sense turbulence above the laser beacon, and our ability to sense turbulence below the beacon diminishes as we get closer to the beacon. Second, as we move to points on the telescope's aperture out from directly under the beacon, we begin to sample the wrong atmospheric path. Light rays from the laser beacon and a star travel along different atmospheric paths. At points on the aperture of a large telescope where the angle between these rays is as large as the isoplanatic angle (2-10 arc seconds), we will make significant errors using the laser beacon vs. a natural star or a beacon at the object. These effects are known as focus anisoplanatism.\textsuperscript{14}

The quantitative impacts of focus anisoplanatism have been analyzed by several workers.\textsuperscript{15,16} Fried and Belsher's work provides useful insight. They found that the mean square wavefront sensing error caused by focus anisoplanatism is proportional to the 5/3 power of the telescope's aperture diameter. They defined a constant of proportionality, $d_0$, such that

$$E^2 = \left( \frac{D}{d_0} \right)^{5/3}$$

where $E^2$ is the mean square higher-order wavefront sensing error in radians\(^2\), $D$ is the aperture diameter, and $d_0$ is the constant of proportionality. This theory has been verified experimentally.\textsuperscript{17} The parameter $d_0$ is a good indication of how effectively the laser beacon adaptive optics system will compensate the higher-order wavefront distortion. When the numerical value of $d_0$ is twice that of the aperture being compensated, the residual wavefront error due to focus anisoplanatism is less than 1/10 of a wave, rms.

The value of $d_0$ depends on the laser beacon altitude, the vertical profile of the refractive index structure constant $C_n^2$, the wavelength of compensation, and the zenith angle of the path through the atmosphere. Tyler\textsuperscript{18} developed a simplified method for calculating $d_0$ given a knowledge of the $C_n^2$ profile, and beacon altitude. Typical values of $d_0$ for good sites are 1.5-2 m for a beacon altitude of 20 km and 4.5-6 m for a beacon altitude of 90 km. These $d_0$ values are for imaging at 0.5 μm directly overhead. Figure 2 shows how the error caused by focus anisoplanatism decreases as the beacon altitude increases. Curves are shown for 3.6 and 8 m telescopes imaging at 0.5 and 2.2 μm. A criterion for excellent compensation is a residual error of less than 1/10 wave. Since many other factors contribute to errors, the error due to focus anisoplanatism should be less than 1/10 wave.

The required laser power can be computed using a lidar-type equation. We need to account for the transmittance of the optics, and atmosphere, the quantum efficiency of the detector in the wavefront sensor, the fraction of the total energy scattered by the atmosphere collected by one subaperture in the wavefront sensor (proportional to $1/R^2$), and the strength of the scattering (the fraction of energy scattered out of the beam toward the telescope per length of scattering volume). For Rayleigh scattering at a wavelength of 0.5 μm at an altitude of 10 km, only 0.05% of the energy is scattered per km of scattering length into a solid angle of one steradian. The scattering coefficient decreases by a factor of $e$ for every increase in altitude of ~7 km. Coupled with the $1/R^2$ loss, these factors make it prohibitive to use laser beacons generated by Rayleigh scattering much above 20 km.

**Figure 2.** Residual higher-order error due to focus anisoplanatism. Sensing error caused by the finite altitude of the beacon for 3.6 and 8 m telescopes imaging at 0.5 and 2.2 μm. Excellent compensation corresponds to a residual error of 0.1 wave or less.

**Figure 3.** Laser pulse energy required to generate a beacon that returns 150 detected photo-electrons in an $r_0$-sized sub-aperture of the wavefront sensor. The parameter $r_0$ is Fried's atmospheric coherence diameter.
The backscatter efficiency of resonant scattering in the sodium layer is considerably more efficient than Rayleigh scattering—being as high as a few tenths of a percent per steradian. However, the $1/R^2$ loss from 90 km is nearly two orders of magnitude worse than for a Rayleigh beacon at 10 km.

Figure 3 is a plot of the laser output energy per pulse required to produce 150 photo-detection electrons per subaperture in the wavefront sensor for a beacon in the sodium layer and a Rayleigh beacon at an average altitude of 15 km. The results are a function of the imaging wavelength and it is assumed that the subaperture size is equal to $r_0$ at the wavelength of interest. For the Rayleigh case, the length of the beacon range gate is $2AH/Sr_0$, where $H$ is the beacon altitude and $S$ is the diameter of the sensing area. This criteria is derived from a requirement that the beacon not be resolved by a subaperture of dimension $r_0$ at the edge of the sensing area. Note that the sensing area for the Rayleigh beacon is only one meter in diameter because of focus anisoplanatism. Multiple Rayleigh beacons will be required to compensate for a large aperture. The problem of combining the information from these beacons is challenging.

The results of Figure 3 are somewhat optimistic since the response of the wavefront sensor to subaperture tilts in the distorted wavefront will be less than that for a true point source at infinity. A detailed analysis of these effects is beyond the scope of this article. Nevertheless, Figure 3 can be used to estimate the total average power of a laser needed to create useful laser beacons. For the sodium case at 0.5 μm imaging wavelength, where it may be necessary to sample wavefront distortions 1,000 times per second, the average laser power is approximately 100 watts. For a 4 m aperture, we would need approximately 10 Rayleigh beacons at about 40 watts each or 400 watts total. However, at 2 μm wavelength, the sodium laser requirement is of the order of a few watts. Figure 3 predicts that the power should be less than a watt since the pulse rate should be proportional to $\lambda^{6/5}$. However, additional power will be needed to make up for loss in wavefront sensitivity caused by sensing with subapertures considerably larger than $r_0$ at the beacon wavelength.

**Experimental Results**

Experimentally, the use of laser beacons is not much beyond a feasibility demonstration and performance evaluation stage. Closed loop experiments have been performed by groups at MIT Lincoln Laboratory,20 the Air Force Phillips Laboratory,21 and Thermo Trex Corp. in San Diego. The Lincoln Laboratory group demonstrated compensation by sending open loop commands to their deformable mirror after a single wavefront distortion measurement from a Rayleigh beacon created by a pulsed dye laser. Thermo Trex also has a low duty cycle system in operation using a frequency doubled Nd:YAG laser as a Rayleigh beacon. Our group at Phillips Lab uses a Rayleigh beacon at 10 km range created by a copper vapor laser operating at 5,000 pulses per second. The high repetition rate laser allows high bandwidth sampling and operation of the control system in a conventional servo mode. We have achieved greater than 100 Hz closed loop bandwidths. The system operates on a 1.5 m telescope, and we typically evaluate the system performance at a wavelength of 0.88 μm. Figure 4 is an example of the performance achieved with this system.

Sodium frequency lasers are very difficult to build since the characteristics of the laser must exactly match the spectral line width and frequency of the mesospheric sodium layer absorption profile. Several innovative sodium lasers have been fabricated22 and initial measurements of signal returns have been obtained.23-25 Sodium frequency lasers usable as beacons for visible wavelength adaptive optics operation remains a significant challenge.

**Future Prospects**

Most development of laser beacon adaptive optics has been for military applications. Now that a decrease in world tensions has relaxed the constraints on military research, there is an excellent opportunity to investigate dual uses of this technology for science and commercial applications. Laser beacons may or may not be appropriate for problems in the civilian community that cannot otherwise use adaptive optics for lack of a suitable beacon—it is too early to know for certain. However, adaptive optics is surely an enabling tech-
nology for many activities in the twenty-first century, and we should push for continued development and research into this important area.

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### References

14. T.R. O'Meara (Hughes Research Laboratory, Malibu, Calif.) introduced the term “focus anisoplanatism.” The term “focal anisoplanatism” also appears in the literature.
19. The sensing diameter could be optimized for a given wavelength of operation, but was kept constant at one meter for this example.