Laser beacon wave-front sensing without focal anisoplanatism

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Wave-front sensing from artificial beacons is normally performed by formation of a focused spot in the atmosphere and sensing of the wave-front distortions produced during the beam's return passage. We propose an alternative method that senses the distortions produced during the outgoing path by forming an intensity pattern in the atmosphere that is then viewed from the ground. A key advantage of this method is that a parallel beam is used, and therefore the wave-front measurements will not suffer from the effects of focal anisoplanatism. We also envisage other geometries, all based on the concept of projecting a pupil pattern onto the atmosphere. © 2002 Optical Society of America

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Laser guide stars (LGSs) offer a means of sensing the distortion of an optical beam traveling in the Earth's atmosphere without the need for a bright natural reference source. Conventionally, the laser is used to project a bright spot in a scattering medium and the backscattered wave front is analyzed with a conventional wave-front sensor as though it came from a point source.[1] This geometry suffers from a number of disadvantages, and the technique proposed here seeks to address two of the main ones. The first is the so-called cone effect, otherwise known as focus anisoplanatism. This effect is due to the different propagation paths from the backscattered laser spot and the target that is being imaged: In the astronomical case, the imaged target samples a cylindrical volume of atmospheric turbulence, whereas the beacon samples a cone. This effect leads to inaccuracies in the wave-front measurement that increase as the ratio of the telescope diameter to the height of the beacon increases. The second problem is that the intensity of the beam at the focus is high, which leads to problems with local saturation of the resonant layer with sodium beacons and to aircraft and satellite safety hazards for Rayleigh beacons.

A number of alternatives to conventional LGS wave-front sensing have been proposed. Baharav *et al.*[2,3] proposed the creation of a fringe pattern in the atmosphere that is analyzed by a Shack–Hartmann wave-front sensor. The problem with this proposal is that high laser powers are required, although this was recently amerliorated by the suggested adaptation of a pyramid wave-front sensor.[4] A recent proposal by Lloyd-Hart *et al.*[5] involved producing a number of images of different planes in the atmosphere as the laser propagates through a focus. These images are then used in a phase diversity wave-front sensor. Angel[6] also proposed a system of dynamically refocusing the laser spot to effectively increase the integration time. All these systems share the common characteristic with the conventional LGS system that the aberrations are sensed during the return downward path of the laser.

Here we propose a different use of a laser to determine wave-front distortions. The sensing concept has a number of different possible implementations, but they all share the common principle that the wave-front aberrations are sensed by the upward passage of the beam. In this Letter we concentrate on one particular implementation, based on curvature sensing, as this has the major advantage of having no focal anisoplanatism. The basic setup is illustrated in Fig. 1. A laser beam is expanded to fill the pupil of the telescope and propagated as a parallel beam upward through the atmosphere. For illustration,

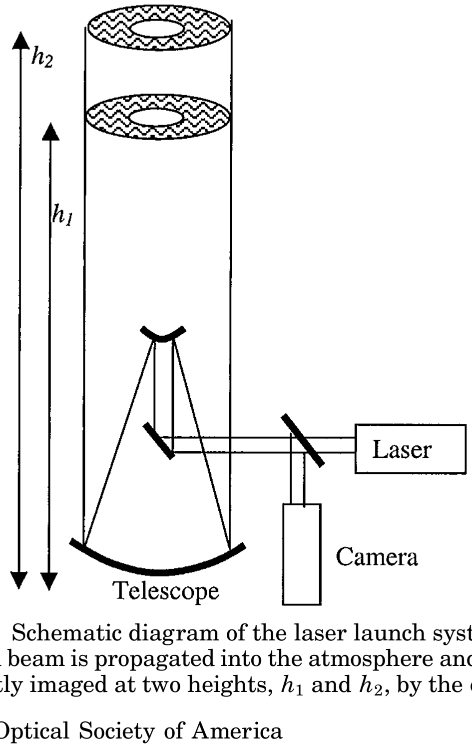

Fig. 1. Schematic diagram of the laser launch system. A parallel beam is propagated into the atmosphere and is subsequently imaged at two heights, h_1 and h_2, by the camera.

we assume that all the atmospheric turbulence is below an altitude of $h_1 = 10$ km. The laser emits pulsed radiation, and when the laser pulse reaches an altitude of h_1 a snapshot of the Rayleigh backscattered radiation is taken with a camera focused at h_1, which will show a disk of illumination corresponding to the telescope pupil. When the pulse reaches an altitude of h_2, 15 km in this case, a second snapshot is taken with a camera focused at h_2. From the propagation-of-intensity equation, we know that points of the laser wave front at 10-km altitude that are locally converging will result in peaks in the intensity distribution at 15 km and locally diverging regions will give rise to local troughs at 15 km. Thus, we can invert the intensity difference between the two images with established methods (e.g., Refs. 7–9) to obtain the wave-front distortion in the upward-propagating laser beam (after applying corrections to the detected images to account for the different scattering cross sections at the two altitudes and the changes in apparent images scale). In this configuration, we have effectively built a curvature sensor,[10] in which the two images of the telescope pupil are formed in the scattering medium.

There are a number of fundamental and practical limitations to this technique: (i) The pupil resolution that is available is limited by the seeing itself. A scattering altitude of 15 km and 1-arcsec seeing correspond to a resolution limit of ~8 cm, i.e., a maximum of 100 × 100 wave-front elements across an 8-m pupil, which is sufficient for even visible-wavelength adaptive optics (when the loop is closed, the number of observable resolution elements will increase). (ii) We are most often concerned with knowing the wave-front distortions that correspond to a stellar beam propagating toward the telescope, whereas the measurands are the distortions of a beam propagating in the opposite direction. In conditions of strong turbulence, this difference can become important, but for many practical situations the turbulence is sufficiently weak that the order in which a collimated beam strikes different turbulent layers is unimportant. (iii) This type of system can clearly work only with a Rayleigh LGS, since multiple-altitude observations are required, although other configurations, which we describe below, are possible with sodium LGSs. (iv) Another factor is the question of the precise location of the observation layers. Atmospheric phase fluctuations should fully evolve into intensity variations over a distance ${r_0}^2/\lambda$, where r_0 is the Fried parameter and λ is the wavelength. In 20-cm seeing at 600 nm, this parameter has the large value of 67 km. Furthermore, a larger r_0 at higher altitudes will result in underestimating the spacing required between planes. Nevertheless, simulations show that intensity fluctuations do evolve to measurable levels over a distance less than ${r_0}^2/\lambda$. (v) This method is similar to the inverse of a technique proposed by Ribak *et al.*,[11] whereby scintillation is used as data for a wave-front sensor. One limitation of this technique was a lack of boundary conditions, and this could also affect the method proposed here. (vi) Finally, we assume that the atmosphere acts as a perfect screen, whereas in reality it will be patchy. A full simulation, including noise, and experimental measurements, which are beyond the scope of this Letter, are needed to fully address these questions.

Despite these limitations, there are many advantages to using this projected pupil-plane pattern (PPPP) configuration compared with a conventional focused-laser-spot approach. The first of these is that focal anisoplanatism can be almost completely eliminated. A second advantage is that the beam power per unit area is much lower than in the focused spot, leading to significantly reduced aircraft hazard in the case of Rayleigh beacons. For example, compared with a 2-arcsec focused spot at 15 km, an 8-m-diameter collimated laser beam of the same power has a beam intensity that is a factor of 10^3 lower.

It is possible to make at least as efficient use of the laser radiation for wave-front sensing when one is using a PPPP arrangement as when one is using conventional focused-laser-spot beacons. Consider, for example, a laser pulse of energy E that is being used to determine the wave-front distortions across a telescope of diameter D with an n element wave-front sensor. Assuming that the return pulse is time gated to allow the radiation scattered between heights $h - \Delta h/2$ and $h + \Delta h/2$ in both cases, the returned energy, e, for both the conventional and the PPPP arrangements is given by

$$e \approx \frac{1}{16} E \left(\frac{D}{h} \right)^2 \frac{\tau(h)}{L} \Delta h \,, \tag{1}$$

where $\tau(h)$ represents the unitless backscattering efficiency for the atmosphere at height h and L is the total length of the pulse. In both cases, we split this energy n ways to determine the wave-front deformations over n different patches in the pupil, so the energy available to measure each degree of freedom in the wave front is given by

$$\frac{1}{16} E \left(\frac{D}{h} \right)^2 \frac{\tau(h) \Delta h}{nL} \,. \tag{2}$$

The curvature-sensing arrangement presented above is only one possible way of forming a wave-front-sensing pattern from an outward-propagating beam. Any arrangement that converts wave-front phase aberrations into intensity variations in the outgoing beam can be used. Figure 2(a) shows an alternative arrangement based on a point-diffraction interferometer. In this arrangement the laser beam is split into two parts. One part is expanded to the full width of the telescope pupil, and the second part is projected as a narrow reference beam of width w. At an altitude of $z \sim w^2/\lambda$, the narrow beam will begin to diffract with a divergence angle of λ/w, and when an appropriate value of w is chosen, the collimated and diverging beams will overlap and be approximately the same diameter, forming interference fringes. By modulation of the phase difference between the two beams, the phase of the wave front at any point in the projected pupil can be inferred from the time variation

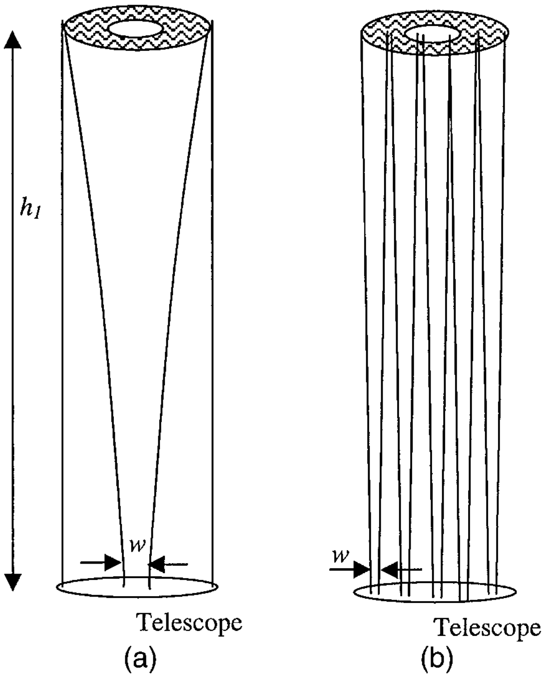

Fig. 2. Schematic arrangement to produce a point-diffraction interferometric PPPP, using (a) a single reference beam and (b) multiple reference beams. The configuration shown in (b) has a reduced cone effect compared with the configuration in (a).

of the fringe pattern intensity at that point, by use of, for example, four-bucket interferometry techniques (although this may be difficult when one is also trying to range gate the laser). The pupil aberrations that are thus measured are the difference in the turbulent aberrations seen by the reference and the main beams. At low altitudes the reference beam is narrow and thus is relatively unaffected by turbulence, but turbulence at altitudes above which the reference beam begins to diverge will suffer an aberration that is correlated with the aberration in the expanded beam. Thus, this arrangement does suffer from a version of the cone effect, where the sensitivity to turbulence varies roughly linearly with height.

The amount of this effective focal anisoplanatism can be reduced by the modification shown in Fig. 2(b), in which the pupil is effectively split into a number of subpupils, each of which has a reference beam. The advantage afforded by this modification is that w can be increased so that the beam does not begin to diverge until it reaches some greater altitude. For instance, we can consider a sodium-beacon system in which the interference plane is at $h = 90$ km and $\lambda = 689$ nm. Using a single reference beam will require a value of $w < 8$ mm if the reference beam is to overlap the entire 8-m pupil at an altitude of 90 km. This beam will begin to diverge at an altitude of $z \approx 90$ m. Splitting the pupil into 1-m subpupils would allow a value of $w = 6$ cm, and thus the reference beams do not begin to diverge until an altitude of $z \sim 5$ km. By modulation of adjacent reference beams (care must be taken since range gating is also being performed) at different frequencies, the phase differences between the reference beams can be deduced at the same time as the difference between each reference beam and the local region of the expanded beam, allowing the wave front across the entire pupil to be accurately determine.

In conclusion, we have proposed a new method of using laser guide stars to project an intensity pattern on the atmosphere that is produced on the upward-propagating path of the laser through the atmosphere. This approach has the advantages of reduced laser power densities in the atmosphere and no focal anisoplanatism for certain configurations. We are in the process of experimentally verifying such an approach.

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