Concept for a laser guide beacon Shack–Hartmann wave-front sensor with dynamically steered subapertures

Christoph J. Baranec

Center for Astronomical Adaptive Optics, University of Arizona, Tucson, Arizona 85721

Brian J. Bauman

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550

Michael Lloyd-Hart

Center for Astronomical Adaptive Optics, University of Arizona, Tucson, Arizona 85721

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We describe an innovative implementation of the Shack–Hartmann wave-front sensor that is designed to correct the perspective elongation of a laser guide beacon in adaptive optics. Subapertures are defined by the segments of a deformable mirror rather than by a conventional lenslet array. A bias tilt on each segment separates the beacon images on the sensor's detector. One removes the perspective elongation by dynamically driving each segment with a predetermined open-loop signal that would, in the absence of atmospheric wave-front aberration, keep the corresponding beacon image centered on the subaperture's optical axis.

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For the next generation of giant telescopes, adaptive optics (AO) that gives high-resolution access to the majority of the sky will be essential.[1] Inasmuch as natural guide star AO systems are severely limited in sky coverage, laser guide stars (LGSs) will be required.[2] Furthermore, as a single LGS, even at the high altitude of the mesospheric sodium layer, suffers unacceptably from focus anisoplanatism, multiple lasers will be needed, with stellar wave-front errors recovered by use of a tomographic reconstruction algorithm.

Early research by Fugate *et al.*[3] demonstrated the practicality of LGSs, and, more recently, sodium resonance beacons were successfully deployed at the Shane and Keck telescopes.[4,5] Already the Keck telescope at 10-m diameter, with a side-mounted laser projector, suffers from perspective elongation,[6] an effect that arises when the length of the beacon column imaged onto the wave-front sensor (WFS) is greater than the telescope's seeing-limited depth of focus. Subapertures far from the laser projector see the illuminated column slightly from the side and image it as a line, compromising the sensitivity of the WFS.

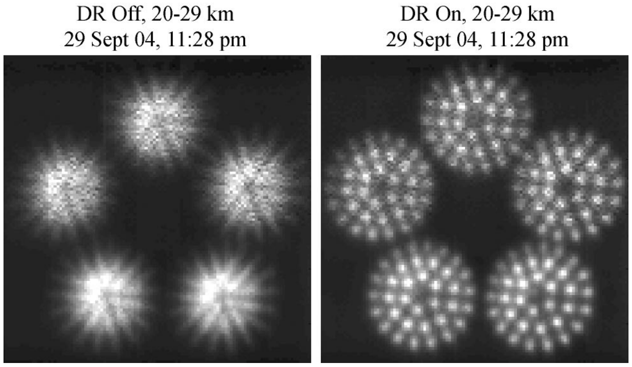
A simple solution is to shutter the WFS detector such that it captures light returning only from a restricted range of height. The full seeing-limited depth of field, f, of a telescope of diameter D focused at height H, calculated from geometric optics, is

$$f = 2H^2 s/D, \tag{1}$$

where s is the seeing disk's width in radians, which we take to be equal to the acceptable amount of blur contributed by defocus. In seeing of 0.5 arc sec, a 30-m telescope using sodium LGSs would be restricted to a range gate on the WFS of $\sim$1300 m. Most of the backscattered light would therefore be lost.

Several strategies for overcoming perspective elongation without making such a sacrifice have been suggested.[7–9] Georges *et al.*[10] have successfully demonstrated a technique in which a sinusoidally driven mirror in the WFS optical train dynamically compensates for the change in focus of the image of a rising laser pulse. A system using this technique to compensate for five Rayleigh LGSs has been installed at the 6.5-m MMT telescope, with the beams launched from behind the secondary mirror, where it is now being used in tests of tomographic wave-front sensing for 30-m class telescopes.[11–13] A single dynamic refocus mechanism serves all five beacons and allows a range gate on the WFS of 20–30 km, more than an order of magnitude larger than the telescope's depth of field. After dynamic refocus correction, a Shack–Hartmann WFS images the five spot patterns onto a single CCD (Fig. 1).

Bauman[14] describes an alternative to dynamic refocus that uses a deformable mirror (DM) by placing a segmented microelectrical mechanical system (MEMS) mirror at an image of the telescope pupil in front of a Shack–Hartmann WFS. The lenslets of a standard Shack–Hartmann WFS divide the full aperture and form separate images of the reference beacon from each subaperture onto a detector. In Bauman's design, the same result is achieved by dynamic tilting of the individual MEMS segments to steer the light from each subaperture according to that subaperature's perspective elongation. We suggest here an extension of this technique in which the functions of perspective elongation removal and the WFS lenslet array are combined in a single unit. This approach also offers the potential to correct both fixed and dy-



DR Off, 20-29 km
29 Sept 04, 11:28 pm

DR On, 20-29 km
29 Sept 04, 11:28 pm

Fig. 1. Shack–Hartmann images of five Rayleigh LGSs at the MMT without (left) and with (right) dynamic refocus. The range gate in both cases was 20–29 km. Each image is an average of approximately 20 s of data recorded at 50 Hz.

namic non-common-path wave-front errors. A single lens following the DM would then form the images from all the subapertures.

Compensation for the global focus term that causes perspective elongation by correcting the induced local tilt over each subaperture is adequate if the subaperture's seeing-limited depth of field is greater than the beacon's column length. We take H to be the mean beacon range and f to be the maximum thickness expected for the sodium layer of 15 km and substitute the dimension of a subaperture, d, in place of the telescope diameter in Eq. (1); then, in seeing of 0.5 arc sec, a 30-m telescope could use subapertures as large as ~2.5 m before individual Shack–Hartmann spots began to be noticeably blurred. For the MMT, with 50-cm subapertures and its lower-altitude Rayleigh beacons, the same criterion permits a range gate from 20 to 27.5 km.

The requirements for the DM are a function of the telescope and subaperture dimensions and of the range and the range gate, r, of the LGS. Segments that define subapertures at the edge of the pupil will change in angle the most. If each segment pivots about its center, then the full mechanical stroke, x, of the mirror required at the edge of the segment is given, to within the small-angle approximation, by

$$x = \frac{\mathrm{d}(D - d)r}{8H^2 - 2r^2}. \tag{2}$$

In Table 1 we list the stroke requirements for DMs for Rayleigh beacons on the MMT and for sodium beacons on two proposed telescopes, the Giant Magellan Telescope (GMT), and the Thirty Meter Telescope (TMT). In each case the subaperture size is taken to be 0.5 m.

The frequency of oscillation of the DM segments must match the pulse rate of the beacon lasers. At a minimum, this must be 1 kHz for adequate temporal sampling of the changing atmospheric aberration, although candidate technologies for sodium lasers prefer higher rates. The simplest way to move the DM segments is sinusoidally at the laser pulse rate, setting the phase and amplitude of the motion to match as closely as possible the changing tilt of the LGS wave front. Figure 2 shows an example of the tilt motion required of a DM segment defining a 0.5-m subaperture at the edge of the GMT, with a sodium laser pulsed at 3 kHz.

We have calculated in Table 1 the required sinusoidal motion for the three cases at 3 kHz. Results are shown for semiamplitude A and acceleration a at the edges of the outermost segments. Also shown is the root-mean-square mismatch in tilt compensation, B, weighted by the expected photon return from each height, which constitutes a residual perspective elongation. For the sodium LGS, B is negligible compared with the expected seeing-limited size of the beacon images, although some radial streaking may remain for the MMT's Rayleigh LGS. In that case, B can be reduced by an order of magnitude if the second harmonic at 6 kHz is included in the DM driving signal with an amplitude of 20%.

Note that, in a sodium LGS, a large focus term is introduced with zenith angle because of the changing distance to the sodium layer. This term would be removed, as in present sodium LGS systems, by explicit refocusing of the WFS. The required amplitude of the oscillation to remove perspective elongation decreases off zenith (Fig. 2). This allows a larger duty cycle to match the longer pulse return caused by the apparent increase in layer thickness without substantially increasing B.

Two technologies may fulfill the requirements for the DM: MEMS and stacked-actuator mirrors that use piezoelectric (PZT) actuators. MEMS have the advantage of being compact, but the technology is too immature for the present application because of limited actuator count and stroke. A conventional PZT actuator mirror, however, could be constructed with present technology. With segments of ~5 mm size, such a DM for a 30-m telescope with 0.5-m subapertures would be 30 cm in diameter, giving an angular magnification of just 100×. This would allow a single DM to compensate for all LGS in a field of at least 10 arc min, the widest field contemplated for ground-layer AO.

We have verified in the laboratory that the physical demands listed in Table 1 are well within realistic limits for small PZT-driven segments. We tested a

Table 1. Stroke and Oscillation Requirements for a Segmented DM

Telescope	Range (km)	D (m)	$x(\mu\text{m})$	$A(\mu\text{m})$	a (g)	B (arc sec)
MMT	20–27.5	6.5	5.1	4.9	176	0.45
GMT	85–100	25.4	2.7	1.5	58	0.06
TMT	85–100	30.0	3.3	1.9	69	0.07

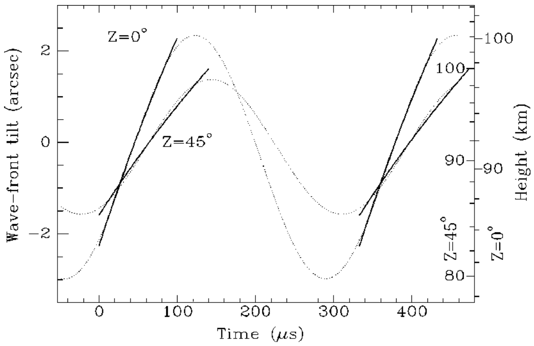


Fig. 2. Sinusoidal radial tilt motion of the wave front from a DM segment defining a 0.5-m subaperture at the outer edge of the GMT (dashed curves) matched to the tilt of the wave front from a sodium LGS pulsed at 3 kHz, returning from 85- to 100-km altitude (solid lines). Zenith angles of 0 and 45° with corresponding height axes at the right are shown; B is 0.06 and 0.08 arc sec, respectively.

4×4 element DM made by Trex Enterprises (San Diego) with 7.5-mm square glass segments mounted on triaxial PZT actuators. During 16 h one segment was driven in tilt at 3.2 kHz with a semiamplitude of 4.3 μm, giving a peak-to-valley wave-front tilt of 4.6 mrad. The edge acceleration in this case was 175 g. In practice, the segment motion must be well controlled to avoid introducing spurious signals into the wave-front measurements.

In Fig. 3 we sketch the conceptual layout of a practical WFS in which a single DM compensates for several LGSs arranged in a ring. To reduce the field requirement, a periscope assembly brings the light from each LGS closer to the axis. By allowing the outer mirrors of the periscope to move radially, we can switch the diameter of the LGS ring from a configuration appropriate for multiconjugate AO, at ~2 arc min, to a configuration for ground-layer AO, at ~10 arc min, without changing the spacing of the Shack–Hartmann patterns on the detector. A field lens puts the entrance pupil at infinity, so the optical train behind the periscope can be moved axially to compensate for changes in focus caused by reconfiguring the periscope and, for sodium LGS, the distance to the sodium layer.

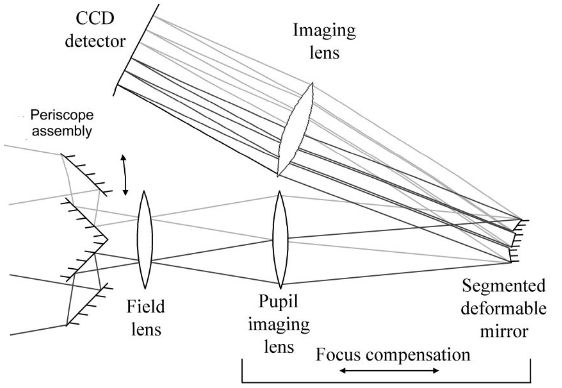


Fig. 3. Conceptual design of a multiple-beacon wave-front sensor for the MMT, showing just 3 DM segments. Not to scale.

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