STEWARD - 1051

Fermilab Library
0 1160 0015655 8

FERMILAB
MAY 2 1992

PREPRINTS

of the

STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA 85721 U.S.A.

No. 1051

RETURN TO FERMI LIBRARY

USE OF NATURAL STARS WITH LASER BEACONS FOR LARGE TELESCOPE ADAPTIVE OPTICS

J. R. P. Angel

Steward Observatory
University of Arizona
Tucson, Arizona 85721

Proceedings of the Laser Guide Star Adaptive Optics Workshop
Phillips Laboratory
Kirtland Air Force Base
Albuquerque, New Mexico
March 10-12, 1992

Use of natural stars with laser beacons for large telescope adaptive optics

J. R. P. Angel

Steward Observatory, University of Arizona, Tucson, AZ 85721

ABSTRACT

Adaptive correction of 8 m class telescopes to the optical diffraction limit requires that the low order atmospheric aberrations, which have the largest amplitude, are corrected with high accuracy. Laser beacon methods of wavefront reconstruction may be inadequate because of errors, from focus anisoplanatism and inherent in slope integration over large spatial scales. Since a natural star must in any case be used in conjunction with a laser beacon to measure overall wavefront slope, we suggest that focus, astigmatism and other low order terms be derived also from starlight. To take advantage of the spatially coherence of the stallar wavefront, we are developing and testing interferometric methods that will yield phase errors directly and accurately over large scales. A complete system would use a fast inner servo loop closed around a laser beacon reference. The resulting image sharpening allows the use of very faint natural stars in an outer loop, to complete the correction to the diffraction limit. An estimate of limiting magnitude shows the probability of finding a random field star bright enough for tilt measurement of a perfectly flattened wavefront would be about 6%, while for a ten times brighter star needed for low order correction the probability is 2%. These estimates assume optimized array detectors are available from 0.7 to 2.2 microns wavelength.

INTRODUCTION

Adaptive optics will be most advantageous when applied to the new generation of large telescopes. The time scale for operation of these telescopes is very soon, with the segmented Keck telescope coming on line this year, and the first large monolithic mirror telescope scheduled for first light in 1994 when the six 1.8 m mirrors of the MMT are replaced with a 6.5 m mirror.[1] The first honeycomb blank of this size was cast on April 3, 1992 at Steward Observatory Mirror Lab. Adaptive optics is planned as an integral part of the instrumentation for the new MMT.

Corrected to the optical diffraction limit with adaptive optics, the new telescopes will have quite extraordinary power, with higher resolution and larger light grasp than the corrected Hubble telescope. However, the task of obtaining full correction at optical wavelengths will tax our skills and technology to the limit. In particular, every scrap of information about the atmospherically distorted wavefront should be used efficiently. At this conference the major topic is the use of laser beacons to sense wavefront errors. It is clear that the large telescopes will need to make use of such beacons. However, their correction cannot be completed without additional information obtained from a natural source, the object under study or a nearby field star.

It is well known that laser beacon methods measure only differential slope errors, and that a natural star is needed to determine the overall tilt component of wavefront error. We argue in this paper that natural stars will be extremely important also for the measurement of large scale low order aberrations such as defocus and astigmatism. Our research program described at this meeting by Lloyd-Hart et al.[2] is aimed specifically at field star wavefront sensing techniques that complement rather than duplicate laser beacon capabilities. We are using the present MMT to make experimental measurements of the wavefront on scales up to 7 m, and to develop equipment and techniques that will carry over to a complete adaptive optics system for the 6.5 m filled aperture.

MEASURING LARGE SCALE ERRORS IN THE ATMOSPHERIC WAVEFRONT

Suppose perfect tilt correction has been made with the aid of a natural star. The magnitude of the residual error is given by Kolmogorov theory and increases with telescope aperture. Thus the rms residual phase error is given by[3]

$$\sigma = .361\ (D/r_0)^{5/6} \text{ radians}$$

For example, a typical value for r_0 at optical wavelengths in good seeing is 0.2 m. The corresponding rms wavefront error will be 7.8 radians for an 8 m telescope, but only 1.9 radians for a 1.5 m telescope. Correction to an rms error of 0.5 radians (78% Strehl ratio)[3] requires a factor 4 improvement for the 1.5 m, but a factor of 16 for the 8 m. Most of the error is at low spatial frequencies, predominantly in the terms of focus, astigmatism and coma.

How well can we expect beacon methods to measure such low order aberrations? The needed improvement in wavefront error is much higher than has been achieved to date by beacon methods, (typically factors of 2 - 4), and is likely to remain very difficult to realize. Systematic errors in large scale slope errors result from the cone effect of focus anisoplanatism. Even if this is removed by use of multiple beacons, there will remain an uncertainty in the magnitude of slope values because of the uncertain heights of the aberrating layers. The height of the layers is about 10% of a sodium beacon height, and can lead to systematic errors at the 10% level in slope, and hence in aberration measurements. Random errors in the reconstructed wavefront will increase with the size of the integration that provides the reconstruction. In simple terms, a large and bumpy wavefront aberration is very difficult to reconstruct accurately over large distances, when the only data are local slope measurements of a diffuse beacon spot, of order one arcsecond in angular size and at finite distance.

The solution we envisage is a double servo control system, in which the inner loop is closed around the wavefront measured by the laser beacon, and an outer loop around a natural star. The outer loop will sense and control low order aberrations as well as overall slope. To be most valuable for astronomical research, the sensitivity of the natural star wavefront measurement must be as high as possible, so as to increase the probability of finding field stars close by, within the isoplanatic angle for shared low order aberration. We here consider three important factors: the most accurate and efficient ways to sense low

order aberrations; detectors that will use the strong infrared flux of field stars; and the likely magnitude limit and corresponding probabilities of finding random field stars within the isoplanatic angle.

INTERFEROMETRIC WAVEFRONT SENSING OF UNRESOLVED STARS

Natural starlight has two advantages for the measurement of large scale errors. Beside the lack of error from focus anisoplanatism, the light is spatially coherent. Thus interferometric methods can be used to measure directly phase differences across the entire wavefront. Conventional wavefront sensors, designed to work with laser beacons that are incoherent, do not exploit this property. Methods such as the Shack Hartmann sensor[4] and small shear interferometry[5] measure local wavefront slopes, and realize large scale measurements by integration across the wavefront.

In the optical shop interferometric methods are heavily favored because of their accuracy. For example, Burge[6] recently measured the same mirror surface by interferometric and slope integrating methods, (pentaprism test). Extreme care was needed to avoid systematic errors with the pentaprism test, and to reproduce the large scale structure revealed in a single interferometric map. It is our expectation that direct interferometry will also prove the most accurate method for measuring large scale errors in the stellar wavefront.

The Smartt point interferometer[7] could in principle yield directly interferometric measurements of stellar wavefronts of the same quality as shop measurements, but the use of one speckle to form the reference beam makes very inefficient use of the light. High efficiency will result if use is made of the full speckle pattern exhibited by the instantaneous image of an unresolved star, the result of interference effects across the full aperture. Under normal conditions the speckle pattern from an 8 m telescope will contain hundreds of speckles, and the task of deducing the wavefront aberration from the speckle pattern may be impossible. However, once the laser beacon loop is closed, its effect will be to improve the wavefront slope errors dramatically, yielding a much smaller and brighter speckle pattern. Recent work by Sandler et al.[8] and Angel et al.[9] indicates that artificial neural nets can be trained to give an accurate wavefront reconstruction from far field speckle images, provided they are not too complex.

Suppose for example that the seeing is initially 0.5 arcsec, and the laser beacon control loop corrects slope errors by a factor 5, resulting in 0.1 arcsec integrated images. For a 2.5 m telescope in the R band, image motion (tilt) is the dominant residual aberration, because the effective r_0 of the corrected wavefront is larger than 1/3 the telescope diameter, and tilt correction alone from a field star would recover the diffraction limit of 0.05 arcsec. However, an 8 m telescope similarly corrected will show an instantaneous 0.1 arcsec image with a dozen or so speckles at the 0.02 arcsec diffraction limited resolution. Given simultaneous images formed at two slightly different focal positions, the neural net method has been shown to work at this level of image complexity. It could be used to obtain the residual wavefront aberration, providing a signal for the outer servo to correct to the full optical diffraction limit.

Our group is exploring this and additional interferometric methods at the MMT, including Fourier transform and phase closure methods,[2] and a phase shifting version of the Smartt interferometer. However, the neural net method has the advantages of simplicity and of closing the loop completely around the final image. It appears that it may be the most photon efficient, but this needs to be shown. It is clear from our experiments with adaptive control closed through a neural net[10] that the net works very well if trained with exactly the images recorded under the prevailing conditions at the telescope. Thus an independent and accurate interferometric wavefront sensor to provide in-situ training data from a bright star will be valuable.

DETECTORS

In order to control the power requirements of laser beacons, imaging detectors with high efficiency at 600 nm are required. For the maximum sensitivity to field stars, very broad wavelength cover, below and above 1 micron wavelength is required. In the past photocathode based imaging sensors were preferred. Now silicon detectors offer near unity quantum efficiency and good response to 1 micron wavelength. We have developed a new small format CCD optimized for wavefront sensing, with 3 msec readout time at 3 electrons rms noise.[2] If required, even lower noise and faster response can be obtained with arrayed silicon avalanche detectors, but only very small formats are presently practical.

Our experimental program at the telescope presently makes use of a 58*62 pixel indium antimonide array with a 100 Hz frame rate readout for wavefront sensing at wavelengths 1.2-2.4 microns.[11] The noise is high, 300 electrons rms, however the rapid advances in infrared array detectors hold the promise of photon noise limited detectors in the near future. We will incorporate a NICMOS3 detector into a new system operating at 30 electron rms noise, and plan to investigate new small format infrared arrays with noise less then 10 electrons.

LIMITING MAGNITUDES AND PROBABILITIES OF FINDING FIELD STARS

Predictions of the limiting magnitude depend on many assumptions about seeing conditions, detectors, throughput and so on, so we will not attempt here a detailed analysis. However, elementary considerations show the probability of finding field stars useful for low order correction is not prohibitively small, even for optical imaging with an 8 m telescope. As a baseline we show in Table 1 a compilation of the magnitude that must be reached in different wavebands to reach a field star density of 1000 stars per square degree at mid-galactic latitudes of 30 - 40 degrees. From the star count data of Bahcall and Soniera[12] we find that a star density of 4000 per square degree will be reached for fluxes 10 times fainter, and 10000 per square degree for fluxes 100 time fainter.

To get a feeling for the field star fluxes required, let us suppose that a good centroid measurement for tilt correction of a fully diffraction limited image recorded from 50 photoelectrons, while ten times this flux is needed to sense a small speckle pattern that will yield low order wavefront analysis. Let us further assume that the atmospheric conditions are such that low order aberrations are shared by a natural star at 5 arcseconds field angle,

Table 1 Field star magnitudes and fluxes in different photometric bands. For each band is given the magnitude m_{1000} that must be reached to find 1000 stars per square degree at galactic latitude 30°-40°. We give also representative values for the sky magnitude per square arcsec. Data for this table was compiled or interpolated from Bahcall and Soniera (1981) and Wainscoat (1991).

Band			Magnitude		Flux (Photons/m²/sec)	
	$\lambda(\mu m)$	$\Delta\lambda(\mu m)$	m_{1000}	sky (per arcsec²)	star	sky (per arcsec²)
V	0.55	0.09	17.3	22	1100	15
R	0.7	0.22	16.6	21	2800	50
I	0.9	0.24	15.5	19	5700	230
J	1.25	0.38	15.2	16	6100	2900
H	1.6	0.40	14.7	15	5300	4100
K	2.2	0.48	14.5	13.8	3400	6500

and a 10 millisecond integration is appropriate for these low order terms. It follows that for an 8 m telescope equipped with very low noise detectors, sensitive to all the photons from a field star, that simple tip/tilt control with a diffraction limited image will be possible or about 10,000 stars per square degree, while low order control will be limited to about 4000 per square degree. For these two densities, the probability of finding a field star within 5 arcseconds of a program object are 6% and 2.4% respectively. These are not large probabilities, but large enough to allow a valuable sampling of many objects. Notice that the requirement for additional photons to allow low order wavefront analysis does not severely impact the chances of finding a field star.

CONCLUSION AND ACKNOWLEDGEMENTS

Field stars alone are not attractive for the correction of optical images of large telescopes, because of the high flux levels required. However, they are especially powerful for the measurement of large scale errors, when used in conjunction with laser beacon methods. Field star techniques currently under development at the MMT take advantage of the unique spatial coherence of starlight and the strong signal at wavelengths larger than μ.

This work has benefitted from many discussions with Michael Lloyd-Hart, Don McCarthy, Dave Sandler, Peter Wizinowich and Nick Woolf. Support for adaptive optics research at Steward Observatory from the Flintridge Foundation and the Director of the Observatory is gratefully acknowledged. The MMT is a joint facility of the University of Arizona and the Smithsonian Astrophysical Observatory.

REFERENCES

1. Chaffee, F. H., Blanco, D. R., Foltz, C. B., Janes, C. C., Lester, H. N., Poyner, A. D., Williams, J. T. 1990, Proc. SPIE, 1236, 507.
2. Lloyd-Hart, M., Wizinowich, P., Angel, R., McLeod, B., McCarthy, D., Colucci, D., Dekany, R., and Wittman, D. 1992, Proc. of the Laser Guide Star Adaptive Optics Workshop.

3. Fried, D. L. 1965, J. Opt. Soc. Am. 55, 1427-1435.
4. Hardy, J. W. 1978, Proc. IEEE, 66, 651 and 1989, Proc. SPIE, 1114, 2.
5. Wyant, J. C. 1975, App. Optics, 14, 2622.
6. Burge, J. 1992, private communication.
7. Smartt, R.N. 1979, Proc. SPIE, 192, 35.
8. Sandler, D. G., Barrett, T. K., Palmer, D. A., Fugate, R. Q., and Wild, W. J. 1991a, Nature, 351, 300.
9. Angel, J. R. P., Wizinowich, P., Lloyd-Hart, M., and Sandler, D. 1990, Nature, 348, 221.
10. Lloyd-Hart, M., Wizinowich, P., McLeod, B., Wittman, D., Colucci, D., Dekany, R., McCarthy, D., Angel, J. R. P., and Sandler, D. 1992, Ap. J. Letters, 390, L41-44.
11. McCarthy, D. W., McLeod, B.A., and Barlow, D. 1990, Proc. SPIE, 1237, 496.
12. Bahcall, J., and Soniera, R. 1981, Ap. J. Suppl., 47, 357.
13. Wainscoat, R. 1991, private communication.