Simulation study of a low-light-level wavefront sensor driving a low-order, near-IR adaptive optics system

DAVID W. TYLER
Rockwell International
Rockwell Power Systems Company
Albuquerque, New Mexico, USA

and

GARY C. LOOS
USAF Phillips Laboratory
Albuquerque, New Mexico USA

Abstract. Two high-fidelity computer simulations are used to study low-order adaptive optics systems operating in the near-infrared. We study obtainable system performance using very dim reference sources at three IR wavelengths.

1. Introduction

Real-time wavefront-reconstruction systems, or adaptive optics (AO), are currently in use at several astronomical sites to overcome the optical effects of atmospheric turbulence. AO systems designed to accurately measure the incident wavefront phase for full correction of visible-light images typically require a bright point-source reference such as a low-magnitude star close to the object or even laser light backscattered from the line of sight. This requirement can either limit the observable objects to those with adjacent bright stars or increase the AO system cost through the need for a powerful laser. Recent work [1] has shown the limited utility of wavefront undersampling to reduce the required reference brightness in visible-light systems; the undersampling itself begins to add significant error to the wavefront reconstruction for spatial sampling rates much smaller than $1/2r_o$, where r_o is the Fried coherence diameter.

However, spatial sampling requirements are not as strenuous for AO systems correcting images in the near-infrared. In fact, diffraction-limited performance at near-IR wavelengths has been achieved on large-diameter telescopes using systems [2,3] that are relatively simple compared to visible-light AO schemes [4]. These systems have already been demonstrated with relatively dim references. Further, low-order systems may be of exceptional value in future long-baseline imaging interferometers [5], where the theoretical resolution is determined by the baseline between telescopes as well as by the interferometer wavelength. In this paper, we use high-fidelity computer simulations to parametrically study the performance of low-light-level AO systems at different IR wavelengths with the goal of finding limiting reference magnitudes for different degrees of AO correction.

2. Simulations

A simulation of a Shack-Hartmann wavefront sensor (WFS) is used to quantify the errors induced by CCD read noise and shot noise, subaperture diameter, and the number of pixels in the subaperture detector array. This simulation includes the effect of increased speckling in the detector plane as the subaperture diameter is increased beyond r_o. A

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detailed description is given in [1]. The product of this simulation is the mean-square value of the difference between the measured tilt and the tilt of a plane least-squares-fitted to the wavefront subtended by the subaperture.

The tilt measurement error is then used as an input in an open- loop adaptive optics simulation. The system geometry in the AO simulation, including subaperture size and actuator spacing, is specified by the user. To approximate a closed-loop, two-mirror system, the WFS subroutines measuring local tilts over the computer-generated wavefront are called twice: once to estimate the full-aperture tilt and, after the tilt estimate is removed from the wavefront, again to estimate higher-order aberrations. After each call, random numbers with variance provided by the WFS simulator described above are added to the each individual local tilt measurement. A complete description of the AO sim can be found in [6].

3. Results

We have simulated the performance of low-order, low- light-level AO systems for a 2-m and 4-m telescope. In the WFS simulation, we assumed the detectors to be shot-noise-limited quadrant cells operating at .7 μm with a quantum efficiency of .1. An exception was made for the smallest subaperture considered in 2-m simulations, where the detector was assumed to have 16 cells. For the 2-m simulations, the diameter of the WFS subapertures are 30, 40, and 49 cm, with an r_o at .7 μm of 15 cm. The actuators were spaced at 40, 60 and 72 cm, respectively, yielding the numbers of subapertures and actuators presented in Table 1 with the rms residual phase errors for the given configurations. Rms phase error with no correction is also shown. For the 4-m simulations, we used diameters of 77 and 63 cm with respective actuator spacings of 1 m and 80 cm. The results are given in Table 2. The IR wavelengths used are 1.0 μm, 1.6 μm (H band), and 2.2 μm (K band). To calculate the number of incident photons in an integration period, we assumed a detector $\Delta\lambda$ = 140 nm and an integration time τ = 10 msec. This τ leads to a closed-loop bandwidth of about 10 Hz, consistent with the existing low-order systems described in [2] and [3]. The visual magnitudes shown are the highest at which reasonable performance was attainable for the configurations studied; 2-4 photoevents per subaperture per interval is typical.

TABLE I
2-M PUPIL

subaps/actuators	1.0 μm	1.6 μm	2.2 μm	reference vis. mag.
no corr.	1.8λ	1.1λ	.8λ	N/A
4/5	.32/.43λ	.2/.26λ	.15/.19λ	m_v = 15.5
8/9	.28λ	.17λ	.10λ	m_v = 15.1
16/21	.3λ	.18λ	.13λ	m_v = 12.9

Rms residual phase error. Where two figures are given, the second is for tilt-removal only.

The significant results for the 2-m simulations are 1.) $\lambda/5$ correction is attainable at 2.2 μm correcting tilt-only at m_v = 15.5, 2.) $\lambda/10$ correction is attainable at 2.2 μm with a system having only 8 degrees of freedom at m_v = 15.1, and 3.) despite the use of a disproportionately brighter reference, there was no improvement using a 16-subaperture system. This last result is due to the increased local tilt variance at the smaller subaperture size. In Table 2, we note that a 4-m telescope operating at 2.2 μm can be corrected to

TABLE II
4-M PUPIL

subaps/actuators	1.0 μm	1.6 μm	2.2 μm	reference vis. mag.
8/9	.42λ	.26λ	.19λ	m_v = 15.5
16/21	.33λ	.21λ	.15λ	m_v = 15.3
16/21	.31λ	.19λ	.14λ	m_v = 14.9

Rms residual phase error.

$\lambda/7$ by a 16-subaperture system using a reference source with m_v = 14.9. In additional simulation, quadrupling the photon flux by using a reference source with m_v = 13.4 yielded rms residual phase error = $\lambda/10$ with the same system. Since the diameter is double that of the 2-m telescope and the rms residual error the same, such a system would double the resolution obtainable with a 2-m telescope corrected by an 8-subaperture AO system at 2.2 μm with reference m_v = 15.1.

References

D.W. Tyler and M.C. Roggemann: 1992, *Proc. SPIE* **1688**, 561
G. Rousset, et al.: 1990, *Astron. Astrophys.* **230**, L29
F. Roddier, M. Northcott, and J.E. Graves: 1991, *Pub. Astron. Soc. Pacific* **103**, 131
M.C. Roggemann, D.W. Tyler, and M.F. Bilmont: 1992, *Appl. Opt.* **31**, 7429
G.C. Loos: 1992, *Appl. Opt.* **31**, 6632
M.C. Roggemann: 1992, *Comp. Elect. Engng.* **18**, 451