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Design Considerations for a Novel Phase-Contrast Adaptive-Optic Wavefront Sensor

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ABSTRACT

The wavefront sensor (WFS) is perhaps the most critical adaptive-optic subsystem, particularly for astronomical applications with natural guide stars, where current WFS sensitivity limitations seriously restrict sky coverage. In this paper, we discuss the possibility of a WFS based on a phase-contrast principle of the sort employed by Zernike for microscopy. Such a WFS would be implemented by inserting a focal-plane filter with a $\pi/2$ phase-shifting central spot having a transverse size of the order of the diffraction limit. The result would be an image of the pupil in which intensity is directly proportional to the seeing- and aberration-induced phase variations over the pupil. In comparison, the signals produced by the two most common current WFS schemes, Shack-Hartmann and curvature sensing, are proportional to the phase slope and to the second derivative, respectively. The phase-contrast approach might derive some advantages stemming from its more natural match to the control eigenvectors of the electrostrictive deformable mirrors that are expected to predominate in high-order adaptive optics systems, in the same way that curvature sensors are currently well matched to bimorph mirrors. It may thus yield substantial performance improvements with simpler hardware and lighter computational loads. We examine this and other possible advantages of the phase-contrast WFS, and investigate some of the practical design issues involved in its implementation.

Keywords: adaptive optics, wavefront sensor

1. INTRODUCTION

As adaptive optics systems have been developed for practical astronomical use, two distinct technological approaches have been dominant[1]. These two approaches are most naturally distinguished by their choice of wavefront sensor (WFS). The Shack-Hartmann WFS reimages roughly r_0-sized subapertures of the telescope pupil onto elements of a lenslet array that focus the light from each subaperture onto a fast, low-noise CCD (r_0 is the transverse coherence scale of atmospheric turbulence). Each focussed spot is directed onto the vertex of four contiguous pixels that act as a quad cell, so motions of the spots measure the aggregate two-dimensional gradient of phase in the various subapertures of the pupil. This approach is currently fashionable for high-order adaptive optics systems with large numbers of deformable-mirror actuators.

A competing technology is based on the "curvature" WFS, in which two significantly out-of-focus images, one on each side of focus, are used to derive the Laplacian (or curvature) of the phase across the pupil. Though curvature systems built to date have happened to employ relatively fewer actuators, it is not clear that the technique cannot perform well in high-order systems, and there are indications that curvature systems achieve better correction per deformable-mirror actuator[2].

The other key hardware component of an adaptive optics system is the deformable mirror (DM), and a number of competing technologies exist here as well. It is somewhat traditional to couple a Shack-Hartmann WFS to a piston-type DM that may operate with piezo-electric stacks or with conceptually-similar electrostrictive material such as PMN. Curvature-WFS adaptive optics systems have traditionally been coupled to deformable mirrors consisting of multiple segments of bi-metallization that respond to an applied voltage by producing a surface figure of proportional curvature. Detailed engineering issues related to how the WFS and DM are aligned produce some well-known effects such as waffle mode, where a checkerboard response mode of the DM is not sensed by the geometry of the WFS, cannot be controlled by the adaptive optics system, and so gradually builds up on the DM to produce a characteristic pattern of four spurious spots in the corrected point-spread function. Beyond geometrical layout, the matching of

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response mechanisms of WFS and DM might be significant: the natural match between second-derivative wavefront sensing and the second-derivative response of the bimorph mirror in curvature adaptive optics systems is thought to explain the rather good demonstrated performance of such systems, on a per-actuator basis, at least in relatively low-order applications.

In this paper, we briefly review several classes of WFS from a fairly general viewpoint, and consider in particular the class of WFS that involves observations of a re-imaged pupil after a filter has been inserted in an intermediate focal plane. This study motivates us to consider a non-standard type of WFS that produces a signal directly proportional to the pupil-plane phase of the wavefront from an unresolved guide star, rather than the first or second derivative of phase as is now common. The approach is essentially a revisiting of the "phase-contrast" technique applied to microscopy by Zernike in the 1930's[3]. In addition to some other advantages, we speculate that a direct-phase WFS might couple well to the piston-type DMs in increasingly common use, which themselves produce phase shifts proportional to applied command voltage. We discuss the focal-plane filter required to achieve phase-contrast operation, and we discuss some practical issues of component manufacture, spectral response, system design, and implementation, proposing minor modifications to an existing Shack-Hartmann adaptive optics system that will allow it to realize a phase-contrast mode.

2. THE CURVATURE WAVEFRONT SENSOR: MEASURING THE SECOND DERIVATIVE OF PUPIL PHASE

The focal-plane image formed by a telescope may be related through a diffraction integral to the general intensity and phase distribution over the pupil of a wavefront incident from a distant unresolved source, which in turn may conveniently be expressed as a two-dimensional Fourier transform:

$$Image(x,y) = |F.T.\{A(\xi,\eta)e^{i\Phi(\xi,\eta)}\}|^2 \qquad (1)$$

Here $A(\xi,\eta)$ in pupil coordinates (ξ,η) is an aperture function representing blockage due to secondary mirror and spiders, while $\Phi(\xi,\eta)$ describes phase aberrations over the aperture. If attenuation of the wavefront is neglected, A and Φ are both real functions. It is apparent from equation (1) that specifying pupil-plane amplitude A and phase Φ will uniquely specify the focal-plane $Image$, but the equation cannot directly be inverted to derive amplitude and phase from an observed image: the squared modulus complicates extraction of phase information. This intractibility can be overcome by curvature wavefront sensing (Figure 1), in which two out-of-focus images are analyzed.

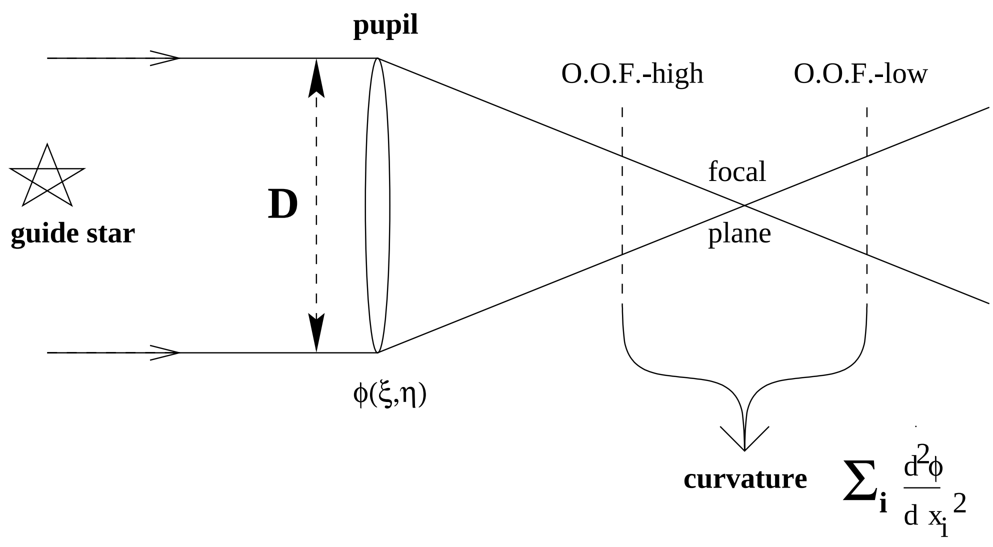

Figure 1. Schematic of the curvature wavefront sensor. O.O.F. denotes (far) out-of-focus images. Heuristically, excess curvature of the pupil wavefront causes patches of the wavefront to focus above or below the nominal focus, so these out-of-focus images contain information on the second derivative of pupil phase.

Beckers[4] gives a non-mathematical, heuristic explanation of how local curvature of a wavefront causes light from that region of the pupil to come to a focus above or below the nominal focus. A complete mathematical formulation for processing out-of-focus image pairs to obtain the second derivative (curvature) of pupil-plane phase, including edge effects, was presented by Roddier[5]. A related technique is phase diversity[6], in which the intractibility of inverting equation (1) with only focal-plane images is overcome by obtaining phase information from one auxiliary image obtained at a small misfocus. Curvature sensing generally involves images with a symmetric and much larger amount of defocus.

3. THE SHACK-HARTMANN WAVEFRONT SENSOR: MEASURING THE FIRST DERIVATIVE OF PUPIL PHASE ON BOTH AXES

The Shack-Hartmann wavefront sensor, shown schematically in Figure 2, is commonly used in many modern high-order adaptive optics systems. The pupil is reimaged onto an array of lenslets, each corresponding to a subaperture size on the telescope aperture comparable to the transverse atmospheric coherence parameter, r_0. The position of the focussed spot from each lenslet is then sensed by four contiguous pixels, configured as a quadrant detector, on a fast, low-noise CCD. More sophisticated multi-stage quadrant-detection schemes are possible, using more than four pixels. The displacement of each spot along the two orthogonal coordinate axes is a measure of the gradient, or first derivative, of the pupil-plane phase over the relevant subaperture.

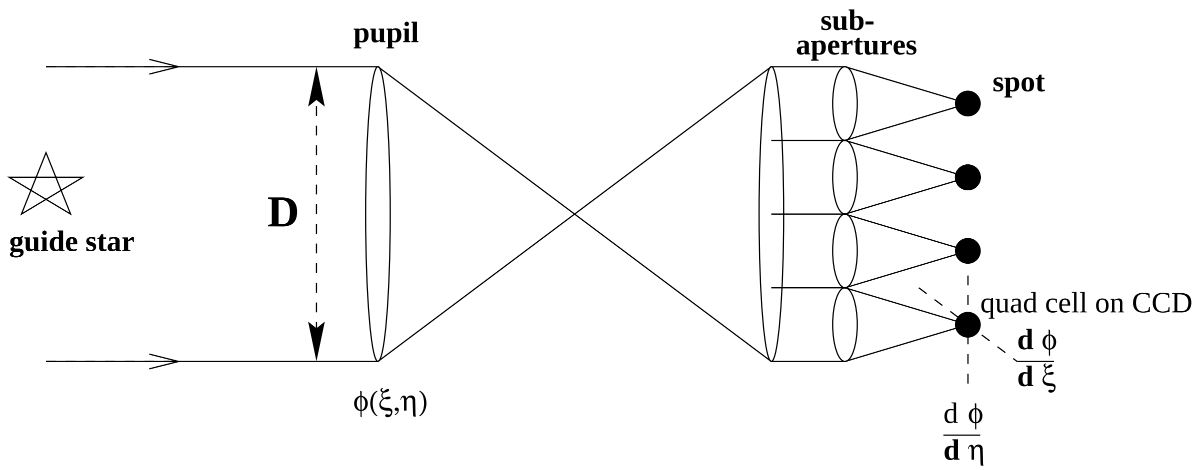

Figure 2. Schematic of the Shack-Hartmann wavefront sensor. Each lenslets in the lenslet array focuses the light falling on individual subapertures onto the vertex of four contiguous pixels of a fast, low-noise CCD. The four pixels act as a quad cell to sense two-dimensional spot motions that correspond to two-dimensional tips and tilts (gradients) in the subaperture phase.

4. THE KNIFE-EDGE TEST: A WAVEFRONT SENSOR THAT MEASURES THE FIRST DERIVATIVE OF PUPIL PHASE ON JUST ONE AXIS

The classic knife-edge (Foucault) test of optics may be used as a quantitative wavefront sensor, although it has the immediate drawback of blocking a substantial portion (nominally half) of the light from the guide star (see the schematic in Figure 3). The knife-edge is inserted in the focal plane, and when the pupil is then re-imaged it shows structure indicative of the phase variations induced by the atmosphere and by static aberrations. (When used as an optical test, aberrations due to imperfections in optical elements or alignment are sensed).

The knife-edge is a focal-plane filter, and may be treated using the machinery of Fourier optics: there is a Fourier-transform relation between the pupil plane and the intervening focal plane, and a similar relation between that focal plane and a subsequent reimaged pupil plane. The effect of inserting the focal-plane filter is to produce light and dark regions in the re-imaged pupil whose intensity is proportional to the first derivative (gradient) of pupil phase with respect to the direction perpendicular to the knife edge.

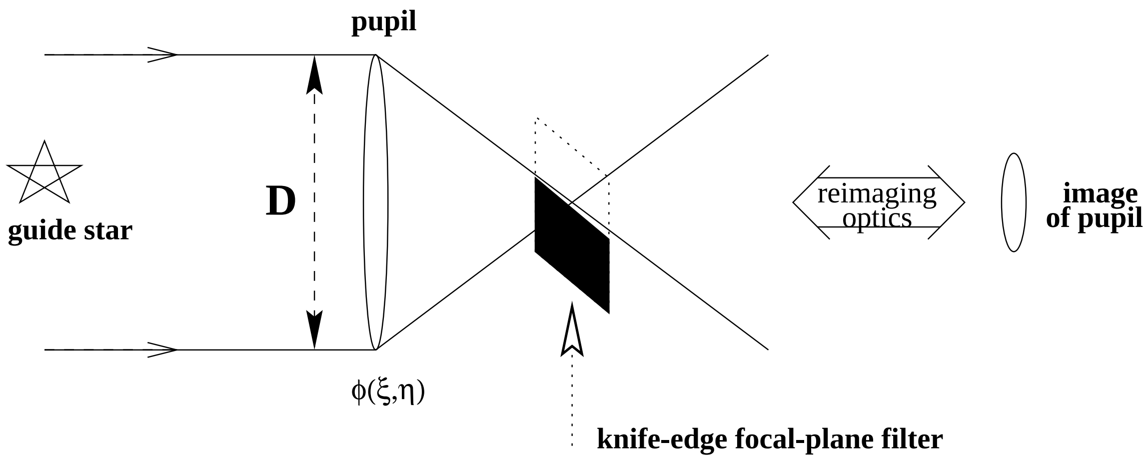

Figure 3. Schematic of the knife-edge (Foucault) test as a focal-plane filter. An opaque screen is inserted into an intermediate focal plane until it obscures roughly half the beam. The reimaged pupil then exhibits light and dark regions whose intensity corresponds to the gradient (first derivative) of the phase with respect to the direction perpendicular to the edge of the opaque screen.

5. AN EXTENSION TO A WFS MEASURING THE ZEROTH DERIVATIVE OF PUPIL PHASE

General considerations of wavefront sensors of different classes, which give response proportional to different derivatives of pupil-plane phase, naturally lead to speculation about what form of wavefront sensor would best couple to the deformable mirrors used in adaptive optics systems. Extremely good performance with a small number of deformable-mirror actuators is achieved by "curvature" wavefront sensors (§2), which measure the second derivative of the wavefront, in combination with bimorph deformable mirrors, which produce surface curvature in response to command voltages. The fact that sense and response are both in terms of the curvature of the wavefront leads to a highly diagonal reconstruction matrix; it may be that this natural match results in a substantial performance boost over systems that command linear phase shifts in response to measured phase slopes (as with a Shack-Hartmann wavefront sensor).

The analogous WFS well-coupled to piston-type deformable mirrors is clearly one that measures pupil phase directly, rather than phase slope or curvature. The problem of directly sensing the phase of a wavefront was solved long ago by Zernike in the context of microscopy. His technique involved inserting a phase-contrast filter in an intermediate focal plane, as is done with the knife-edge filter of §4; the phase-contrast filter is a transmitting spot of optical thickness $\pi/2$ and transverse scale of roughly the diffraction-limited spot size (Figure 4). For small phase excursions, the intensity observed in a given region of a subsequent re-imaged pupil is directly proportional to the phase of the wavefront in that part of the pupil.

6. PRACTICAL CONSIDERATIONS

6.1. Advantages of the Phase-Contrast WFS

In the Shack-Hartmann WFS, measuring the gradient of the wavefront over a given subaperture of the telescope pupil requires dividing the light among four pixels of the WFS CCD, reducing the individual signals and incurring four read-noise contributions. By comparison, in the phase-contrast WFS, light from a given subaperture is concentrated onto a single pixel, reducing in principle the relevant readout noise when the signal is sampled. The situation is probably even worse in the Shack-Hartmann case, as the signal to be measured is not really the four pixel intensities, but two differences of pairwise sums of pixel intensities that give the two-axis centroid motion. This differencing of comparable numbers makes the fractional read noise more significant.

Possibly the most fundamental potential advantage of the phase-contrast WFS over the Shack-Hartmann is the natural match to piston-actuator DMs (whose position is proportional to command voltage) discussed in the previous

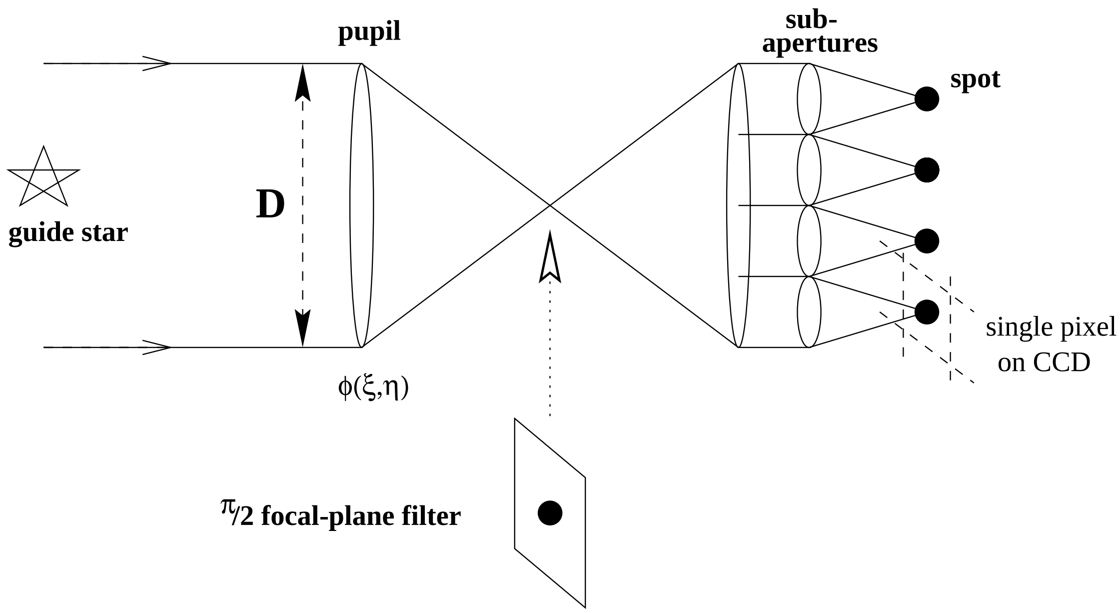

Figure 4. Schematic of the phase-contrast wavefront sensor. A focal-plane filter is inserted into the intermediate focal plane, as with the knife-edge WFS, but the filter in this case is transmitting, so no light is lost. The filter has an additional optical thickness of $\pi/2$, and has a transverse size roughly matching the diffraction-limited spot size. In the reimaged pupil, subaperture spots have intensity directly proportional to the pupil phase in that subaperture, and may thus be measured by a single CCD pixel (see text).

section. If this efficient coupling results in a more efficient adaptive optics system, the benefits will include better correction for a given guide-star brightness, and operation to a fainter guide-star magnitude limit, easing somewhat the main limitation of current natural guide-star systems. The net effectiveness of the phase-contrast mode needs to be investigated through detailed modelling and verified by experiment.

6.2. Fabrication of the Phase-Contrast Filter

A phase-contrast filter could be operated either in transmission, by depositing the $\pi/2$ phase shifting spot on a transparent substrate, or in reflection, by depositing it on a flat mirror. If used in reflection, half the phase thickness is required, as the spot is traversed twice. The spot would need to of transverse dimension corresponding roughly to the diffraction-limited scale of the telescope point-spread function ($\sim \lambda/D$). At visible wavelengths at the $f/16$ Cassegrain focus of the Palomar 200-inch telescope, this scale is roughly

$$\lambda/D \times [(f/\#)D] = \lambda \times (f/\#) \sim (0.5\ \mu m)(16) = 8\ \mu m \tag{2}$$

which is a microfabrication scale easily achieved with modern ultraviolet photolithography, typically governed by sub-micron line rules.

Spot thickness Δx is chosen to give an extra phase of $\pi/2$ or an extra pathlength of one quarter wavelength over the same path through air. Hence, if $n \sim 1.5$ is a typical index of refraction of the deposited spot material at visible wavelengths, one requires $(n-1)\Delta x = \lambda/4$, from which $\Delta x \sim \lambda/2 \sim 0.25$ μm $\sim$ 2500 Å, a substantial but not unwieldy layer thickness for thermal evaporation. Half of this thickness would be used in the reflection-mode focal-plane filter to be discussed for direct insertion into an existing Shack-Hartmann adaptive optics system (§6.3).

A concern with the phase-contrast wavefront sensor is the chromatic nature of the focal-plane spot, which would possibly require restricting the passband of guide-star light in the case of a natural guide star. (Laser guide stars are essentially monochromatic, and present no problem here). The $\pi/2$ phase-shifting focal-plane spot can be fabricated from two or more materials having opposite slopes of refractive index with wavelength, to give a net phase-shift through the stack that is approximately independent of wavelength, in analogy with an achromatic doublet lens.

But the diameter of the spot is also defined for a given wavelength as $\sim \lambda/D$. The overall sensitivity of system performance on the match of spot size to λ/D is a matter for further modelling and experiment. If chromatic effects are important here, it should be noted that restricting the WFS passband has less impact than it would first appear, as the wavefront sensor CCD has a strongly peaked responsivity anyway; so relatively little may be lost by defining a narrower passband centered on the wavelength of that peak.

6.3. Optical Configuration in a Modified Shack-Hartmann Adaptive Optics System

It appears possible to implement a practical phase-contrast wavefront sensor by slightly modifying an existing adaptive optics system based on a Shack-Hartmann WFS. Such a system is PALAO, the Palomar Adaptive Optics Sytem[7–9], for which an optomechanical layout is shown in Figure 5.

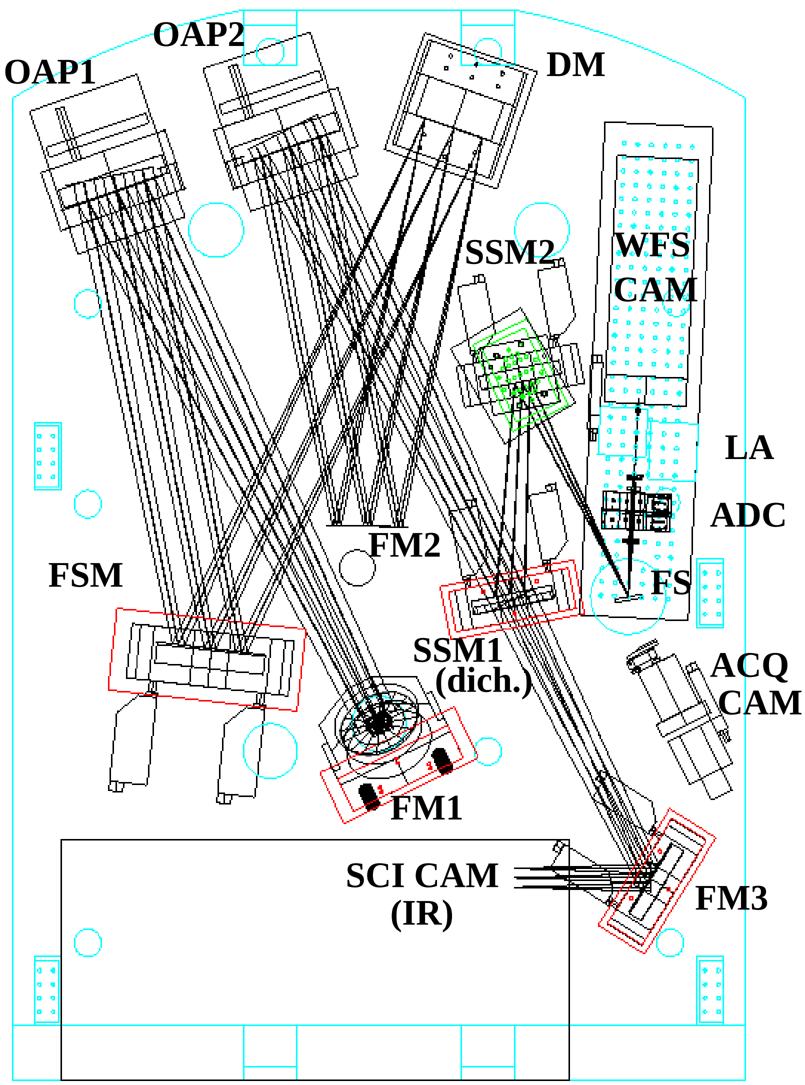

Figure 5. Optomechanical layout of PALAO, the Palomar adaptive optics system, which uses a Shack-Hartmann wavefront sensor. The field stop (FS) affords a convenient accessible focal plane in which the phase-contrast filter may be inserted; adaptation of the WFS CCD to phase-contrast operation is discussed in the text.

The beam enters the optics shown via fold mirror FM1. Visible light to the wavefront sensor is split off by the dichroic, SSM1, and directed onto the field stop (FS), which lies in a focal plane. The field stop consists of a small

(4 arcsec × 4 arcsec) metallization on an otherwise transparent substrate. Light from the guide star is reflected by the metallization into the lenslet array (LA) and then into the CCD (labelled WFS CAM in Figure 5).

A convenient available focal plane for the insertion of the phase-contrast filter is the field stop, FS; a half-height ($\pi/4$) filter here is of course appropriate, as it will be traversed twice as the beam reflects into the wavefront sensor. In closed loop, the visible spot in the plane of the field stop is roughly diffraction-limited and stationary, as it enjoys the correction of the DM and the tip-tilt mirror (FSM). The non-normal incidence of the beam on the field stop gives it a slightly elliptical net footprint on reflection, and a tilted angle of passage that is not easily fitted to the deposited phase-contrast filter. This effect may be small enough in the current configuration that the phase-contrast benefits are still realized, and it might be possible in a future re-engineered optical layout to reduce the angle between incident and reflected beams at the field stop.

In normal Shack-Hartmann operation, the WFS spot size from an individual subaperture in PALAO is roughly the diffraction limit of a single subaperture, or the nominal seeing blur size; these should be about the same, depending on the seeing. Measured spot sizes are about 1.5 arcsec, and the optics of the WFS are arranged so that individual pixel sizes on the WFS CCD are also about 1.5 arcsec.

6.4. Tuning the Overall Phase

With the phase-contrast WFS, the overall average value of absolute pupil phase is no longer ambiguous, as it is in most adaptive optics systems, particularly those directed by Shack-Hartmann wavefront sensors. If the absolute phase is at an inappropriately-chosen value, the on-axis photon count from each subaperture can be small or the sign of WFS intensity versus phase change could be incorrect, making adaptive control impossible. Luckily, this situation is easily remedied by adjusting the overall piston level of the deformable mirror to give adequate subaperture flux in the WFS.

Under normal operation, overall phase would be controlled via overall DM piston to give near-maximal photon flux on the correct part of the WFS intensity/phase control curve.. On startup (see §6.5), the subaperture flux would need to be checked immediately and the DM piston adjusted very quickly to avoid losing lock as control is switched from Shack-Hartmann to phase-contrast WFS. Since the stroke of PALAO's deformable mirror, about 8 μm of wavefront, is many turns of visible-light phase, controlling the overall phase to stay near a phase-contrast peak or linear control region is straightforward.

6.5. Startup of Phase-Contrast Control from Standard Shack-Hartmann

The similarity of the phase-contrast WFS optical layout to that of the Shack-Hartmann WFS now in common use suggests a simple startup and test mode in which the phase-contrast focal plane filter is swapped into operation in place of a Shack-Hartmann that has already achieved a lock. As well, the phase-contrast wavefront sensor traditionally assumes small phase variations, so some means of achieving a decent correction (putting a substantial amount of guide-star light into a diffraction-limited core) is required before it can be inserted in the adaptive optic control loop. Schemes for altering the transverse scale of the focal-plane filter at startup, as the quality of the lock improves, are also possible, but less convenient if an existing Shack-Hartmann system is at hand.

At startup, the phase-contrast spot would be positioned on the field stop a distance from the focussed beam equal to half the subaperture spot size or WFS CCD pixel diameter ($\sim$ 0.75 arcsec) in both axes. At that distance, the phase-shifting spot would have no effect on the diffraction-limited guide-star image (FWHM $\sim$ 0.02 arcsec) on the field stop, and hence no effect on normal Shack-Hartmann operation. To engage the phase-contrast mode from an initial Shack-Harmann lock, the tip-tilt mirror (FSM) of the adaptive optics system would be abruptly commanded to move 0.75 arcsec in both axes, until the guide-star image on the field stop hit the phase-shifting spot; an immediate shift to a new control algorithm base based on the phase-shift WFS would also be made. The subaperture spots would all simultaneously shift to lie entirely within one pixel, rather than on a quad-cell four-pixel vertex.

7. CONCLUSIONS

The discussion here is intended to present some practical considerations for implementing a phase-contrast wavefront sensor relatively easily, starting with an existing standard Shack-Hartmann configuration of the sort now in operation at Palomar Observatory. Such an implementation appears feasible with only modest modifications. More work remains to be done to quantify the possible performance boost that might be realized by coupling a phase-contrast WFS to a piston-type DM of the sort now in use, but general arguments are encouraging.

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