Subaru Coronagraphic eXtreme Adaptive Optics: on-sky performance of the asymmetric pupil Fourier wavefront sensor

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ABSTRACT
The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument relies on a technique known as the asymmetric pupil Fourier wavefront sensor (APF-WFS) to compensate for the non-common path error that affects the performance of high contrast imaging instruments. The APF-WFS is a powerful tool that senses the wavefront at the level of the science detector, and leads to unbiased wavefront estimates. This paper presents the latest status, linearity properties and reports on the on-sky performance of this sensor, as it is implemented on SCExAO, used to control low-order Zernike modes in a close-loop system.

1. INTRODUCTION
The asymmetric pupil Fourier wavefront sensor (APF-Wavefront Sensor) method relies on the analysis of the Fourier properties of an AO-corrected image acquired after an asymmetric hard-stop mask has been placed in the pupil to directly sense pupil phase aberrations. It is now implemented as one of the wavefront control tools of the Subaru coronagraphic extreme adaptive optics (SCExAO) instrument,\textsuperscript{1} to compensate for a non-common path error unseen by its upstream pyramid wavefront sensor.

For small aberrations, the Fourier-phase $\Phi$ is linearly related to the pupil phase $\varphi$, via a unique operator labeled $A$ that depends on the geometry and illumination of the aperture and describes the way the different parts of the pupil map into the UV-plane:

$$\Phi = \Phi_0 + A \times \varphi.$$  \hfill (1)

where $\Phi_0$ represents the Fourier-phase of the target pointed at during the observations. For the purpose of this sensor, the sources targeted for high contrast imaging, that is bright stars surrounded by high contrast structures, can be considered as point sources: just like for SCExAO’s internal calibration source (a fiber-fed super-continuum laser) used to do the acquisition of the response matrix of the sensor, this phase information can be considered to be $\Phi_0 = 0$.

It has been demonstrated that this Fourier-phase relation can be inverted if one introduces an asymmetry in the pupil.\textsuperscript{2,3} A direct focal plane image, with only a small amount of additional diffraction generated by the pupil asymmetry (see Figure 1), can therefore serve as a wavefront sensor:

$$\varphi = A^{-1} \times \Phi.$$  \hfill (2)

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2. MODAL (ZERNIKE) CONTROL

The control of low-order aberration is crucial to reach the full high-contrast imaging performance of a coronagraph with a small inner working angle such as the PIAA.\textsuperscript{4} On SCExAO, the APF-WFS is optimized to control eight Zernike modes (from focus to spherical) that suffice to compensate for the effect of flexures after repointing the Subaru Telescope. The technique is however not restricted to these and can, depending on the acquisition mode, be extended to an arbitrary number of high-order modes.

Figure 2 presents the Zernike modes, from $Z_4$ (focus) to $Z_{10}$ (primary spherical) as they are sensed and reconstructed by the APF-WFS method. One will observe that except for the spherical aberration that is less well reconstructed, the modes extracted from the analysis of a single focal image do closely resemble the theoretical Zernike polynomials.

3. CLOSED-LOOP DEMONSTRATION

3.1 Calibration

The calibration procedure for this implementation of the APF-WFS follows the linear control framework. After the asymmetric mask has been inserted, one image labeled as reference is acquired, followed by a sequence of images acquired after a Zernike mode of appropriate amplitude has been applied to the DM. The calibration data is acquired with the focal camera of SCExAO on its internal calibration source (super-continuum laser) using a standard H-band filter for a 30 nm RMS deformation of the DM. This displacement actually translates into a (doubled) 60 nm wavefront amplitude modulation (the DM being a reflective system).

These experimentally obtained pupil-phase modes $\varphi_i$ are stored in a 8-column response matrix $Z$. In practice, unless the DM registration were to change in a dramatic manner, the calibration is quite robust: a response matrix acquired using the internal calibration source can be very well used during on-sky observations if the filter remains unchanged, and if the change of exposure time does not result in a saturated PSF core.

On SCExAO, the acquisition of this response matrix only takes a few seconds, so it can easily be repeated if necessary after acquisition of a new target. In practice, it seems a response matrix that is acquired using the stable internal calibration source provides the best results.
Experimental Zernike modes

Figure 2. Experimentally recovered Zernike modes. Save for the spherical aberration, the modes extracted from the analysis of a focal image closely resemble the theoretical Zernike polynomials.

3.2 Closed-loop

Just as during the calibration, focal-plane images acquired on-sky with the asymmetric mask are dark-subtracted, recentered, and windowed by a super-Gaussian function before being Fourier-transformed. After extraction of the Fourier phase, a wavefront is produced and directly projected onto the basis of modes (without subtracting the reference), to find the coefficients associated with all eight Zernike components. If the current wavefront sensor signal is $\varphi$, the instant Zernike coefficients ($\alpha$) are the solution of $Z \cdot \alpha = \varphi$. The least square solution $(\hat{\alpha}_i)_{i=4}^{11}$ of this system is the solution to

$$Z^T \cdot \hat{\alpha} = Z^T \varphi. \quad (3)$$

The solution $\hat{\alpha}$ to this well-behaved system of equations is used as an input for a control loop algorithm. The loop in operation on SCExAO implements a simple proportional controller, with a gain common to all Zernike modes with value contained between 0.05 and 0.3, depending on the overall stability of the wavefront provided by the upstream AO. When looking at the internal calibration source, we can reliably use the highest gain. Since, for now, it is only used for a very short time (typically $\sim 15$ seconds), at the time of target acquisition to flatten the static component of the wavefront, the current implementation of the algorithm proves satisfactory. Once the non-common path error is accounted for, the asymmetric mask is taken out of the optical path and the system is ready for observation using the full pupil of the telescope.

Figure 3 shows a result obtained on-sky that compares two $500 \mu$s exposures of the target (Altair) acquired by SCExAO’s internal science camera on UT 2015-10-30. The first image shows the PSF after the AO188 loop has been closed on the target: although it features a well-defined diffraction core, the PSF clearly exhibits some static aberrations that can be attributed to the non-common path error between AO188 and SCExAO’s focal plane. The second image shows the PSF about 30 seconds after the APF-WFS loop has been closed. The gain in Strehl is low (of the order of 5 %), but the PSF is improved at where it matters most for high contrast imaging and no longer features any obvious low-order aberration signature. Residual inhomogeneity of the first
diffraction ring can be attributed to a combination of instantaneous AO residuals combined with the effect of the asymmetric arm.

4. RANGE OF LINEAR RESPONSE

As previously mentioned, the APF-WFS relies on the assumption that an upstream AO correction is provided. The system is expected to deal with with small residual wavefront errors, and the calibration procedure described above, typically employs DM modulation amplitudes of \( \sim 30-50 \) nm (with a doubled effect on the wavefront). To determine the amount of aberration the technique is able to deal with, we performed a systematic exploration of the response of the sensor to stimuli of variable amplitude. The instantaneous response of the sensor is projected onto the basis of modes following the procedure outlined in the section describing the closed-loop operation. Figure 4 summarizes the results of this systematic exploration of the response of the sensor, over a \( \pm 150 \) nm range of DM modulation amplitude.

Although not perfectly linear, for \( Z_4 \) (focus), \( Z_5 \), \( Z_6 \) (astigmatism), \( Z_7 \) (coma 1), and \( Z_{11} \) (spherical), the response remains monotonic over the entire \( \pm 150 \) nm range. For \( Z_8 \) (coma 2), \( Z_9 \) and \( Z_{10} \) (trefoil 1 and 2), the response is only monotonic over the \( \pm 80 \) nm modulation range beyond which the sensor cannot be used reliably. A strong non-linearity of the response is experienced when the pupil-phase peak-to-valley (P2V) wavefront becomes larger than \( 2\pi \) (which results in a phase wrap). The presence of the asymmetric stop at its current azimuth essentially divides the P2V by a factor of two in the case of \( Z_7 \) (i.e. coma 1), hence making the sensor able to handle twice as much coma along the horizontal axis than along the vertical axis. We note that the same effect (to a lesser extent) can also be observed when comparing \( Z_9 \) and \( Z_{10} \). We can nevertheless conclude that, in the H-band under normal operating conditions, the sensor is able to operate linearly as long as the RMS error on either mode is less than 200 nm on the wavefront.

5. CONCLUSION

A surprisingly simple asymmetric hard stop mask introduced in the pupil of a diffraction-limited imaging instrument is proving to be a powerful diagnostic tool for the control of the non-common path aberrations. The reported capture range of the technique is currently limited to a fraction of a wave (RMS \( \sim \lambda/8 \)). While restrictive, the approach is already perfectly suited to the compensation of the non-common path error in the context of extreme adaptive optics as demonstrated on the SCExAO instrument. A simple way to extend the capture range of the technique would be to use a series of filters of decreasing wavelengths to tolerate a cruder starting point. We are currently exploring the potential of an updated algorithm that simultaneously exploits the information sampled at multiple wavelengths to extend the capture range even more, this time within the coherence length.
Figure 4. Experimental response of the APF-WFS measured on the SCExAO internal calibration source. It is nearly linear for most modes over a ±100 nm range covered (except coma 2 and trefoil). Note that these are for the DM surface: values must be doubled if referring to aberrations on the wavefront. While nearly linear over the entire range for most modes, the sensor only exhibits a significant non-linear behavior for the coma 2, and the two trefoil modes when the DM Zernike amplitude is larger than 80-100 nm. We note that this limit is on the DM surface, which must be doubled if referring to aberrations on the wavefront.

We note that other approaches using combinations of non-redundant aperture masks also rely on this idea to extend their capture range.

The use of this wavefront control technique extends well beyond the control of low-order modes on SCExAO: this paper provides experimental evidence that the technique is actually effective where the theory predicts it should be. In an exposure that simultaneously features an unsaturated PSF core and the diffraction features at large separation with sufficient SNR, APF-WFS can be used to control an arbitrary number of modes, as was shown in the concept paper. The APF-WFS can, in fact, be easily applied in a wide variety of wavefront sensing contexts, for ground- as well space-borne telescopes, and with a pupil that can be continuous, segmented, or even sparse. APF-WFS is powerful because it measures the wavefront where it really matters, at the level of the science detector. Given its low impact on the instrument hardware, it is an option that should be given some consideration as part of any high contrast imaging instrument with wavefront control capability.

REFERENCES