High-order AO in the visible: The Durham High-Order Demonstrator

Richard Myers[1], Alastair Basden[1], Nazim Bharmal[1a], Nigel Dipper[1], Tim Morris[1]

Centre for Advanced Instrumentation, University of Durham, UK

Abstract. The Durham High-order Demonstrator (DHD) is a proposed high-order/extreme adaptive optics instrument design for the 4.2 m William Herschel Telescope on La Palma, Canary Islands. Our principal interest in this instrument is designing a flexible-testbed for which we can develop a high-order AO system which is suitable for diffraction-limited, visible-light imaging. Additionally, it then becomes a facility which provides a high-order AO corrected beam for further instrument development such as coronography and thus XAO applications. This paper shows our instrument design and the limiting performance estimates. Part of the high-order wavefront sensing is provided by a second interferometric wavefront sensor of novel design to characterise the PSF and resolve quasi-static aberrations to prevent persistent speckle.

1 Introduction

Adaptive Optics is typically limited to near-IR or longer wavelengths due to insufficient spatial sampling of the wavefront. To achieve high Strehl ratios in the visible requires what will be described as high-order AO; approximately, matching the sampling of the wavefront to the Fried turbulence length-scale r_0 at visible wavelengths. At this level of sampling, and using a suitably high-order deformable mirror to achieve the requisite level of correction, it becomes possible to achieve the diffraction limit of the telescope for wavelengths in the blue part of the spectrum. This in turn offers the possibility to perform high-resolution science about the guide star at the 10 milliarcsecond-scale.

Our interest in such a high-resolution instrument is to further develop our AO technologies to achieve the diffraction limit in the visible for 4 m class telescopes. The availability of several technologies makes the construction of a high-order AO test-bed feasible and as such this paper describes the design of the Durham High-order Demonstrator. Its principal location is at the Ground High-Resolution Imaging Laboratory on a Nasmyth platform of William Herschel Telescope (WHT) [1]. It is designed to apply high-order AO correction to the incoming light to produce a highly corrected PSF that can then be interfaced to other instruments or a dedicated H-band imager. As such, it does not have a specific scientific context but is instead meant as an instrumental development platform.

The basic design is a single conjugate AO configuration using a 30×30 Shack-Hartmann wavefront sensor together with a combined low/high-order 1024-/144- actuator-count DM using joint low-/high-order control. The wavefront sensor will utilise a camera to provide at least 128×128 pixels, for 4 pixels minimum per sub-aperture with a readout rate of $\geq$ 1 kHz. The baseline design is compatible with spatial-filtering of the WFS input to remove aliasing effects. The optical relay is designed for a narrow-field of view of 1” and this makes it affordable to use high-quality optics ($\lambda/100$). As part of the relay, an ADC will also be included. The final dedicated component of DHD is the characterisation wavefront sensor, CWS. This measures the corrected beam, in parallel with the SHWFS, but it is intended to measure the residual wavefront more precisely than the SHWFS. The CWS, described later, is a static interferometer design which has high-gain rather than high-dynamic range. The measurements from this WFS are intended to be low bandwidth, $\sim$ Hz, and so measure the residual offsets for the deformable mirrors because of, for example, SHWFS non-linearity, chromatic aberrations, and pupil rotation. Not including these effects leads to slow phase errors that in turn cause the formation of quasi-static speckle that cannot be integrated out [2]. A final use of the CWS is to characterise the final Strehl ratio that is achieved by the AO correction, thus this capability need not be included in the subsequent instrumentation.

[a] n.a.bharmal@dur.ac.uk

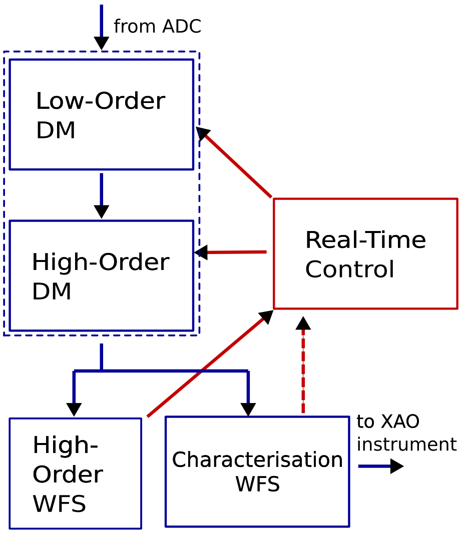

Fig. 1. A block diagram of the DHD optical arrangement. In blue are marked optical components, in red where the real time control interfaces with these components. Note that the Characterisation Wavefront sensor is part of the optics that transfers the beam to the instrument to minimise effects of non-common path aberrations.

The DHD design is shown as a block diagram in figure 1, where the RTC is intended to be the Durham Realtime-Controller [3] which is capable of the required AO loop rate ($\geq$ 1 kHz) using CPU alone. Initially, the corrected beam will delivered to a near-IR camera which will oversample the theoretical diffraction-limited PSF of the WHT by a factor of 2. The beam interface will be clearly defined and so compatible with a variety of instruments that would benefit from the high-order correction: perceived examples include on-sky coronograph demonstrators, novel interferometric methods , or an integral-field spectrograph for implementing speckle rejection techniques.

2 Performance

We quantify the performance of the DHD design using numerical simulation [4] based on the parameters in table 1. The chosen sampling of 30×30 is partly dictated by the 1 K MEMs DM specified, a Boston Micromachines 1024-actuator device [5], but this is also well-matched to the Fried turbulence length-scale at the WHT site in visible wavelengths [6]. The corresponding field of view for which the Strehl ratio is degraded by less than 90 % compared to the on-axis pointing direction is estimated as 0.2”/1.3” in V/H-band. Given these parameters and in idealised conditions excluding non-common path errors, telescope vibrations, and varying seeing, leads to a Strehl ratio of 0.96 with residual wavefront errors of 56 nm RMS. Using the extended Maréchal approximation, this value can be scaled to produce figure 2 which demonstrates that the theoretical limitation of the DHD design is compatible with XAO imaging in the near-IR and diffraction-limited imaging can be maintained upto blue wavelengths.

The availability of a suitable camera is the principle limiting factor in terms of required guide-star brightness and a study was carried out to assess two choices currently available: a CCD-based camera (using a Lincoln Laboratories/MIT CCID 18 chip) and a sCMOS-based camera [7]. The latter has lower QE, a peak of 57% versus a peak of 85%, but also lower readout noise and better near-IR performance. The results are summarised in figure 3 for the same numerical simulation system parameters as before but with varying guide-star magnitude (assuming a flat spectrum). Performance is maintained till $m \simeq 4$ but remains very good for $m = 7$. This permits a wide-variety of targets to be selected for high-order/visible-light AO and a smaller range of targets for XAO-quality correction. Although insufficient for XAO science in itself due to the lack of fully calibrated instrumentation, as

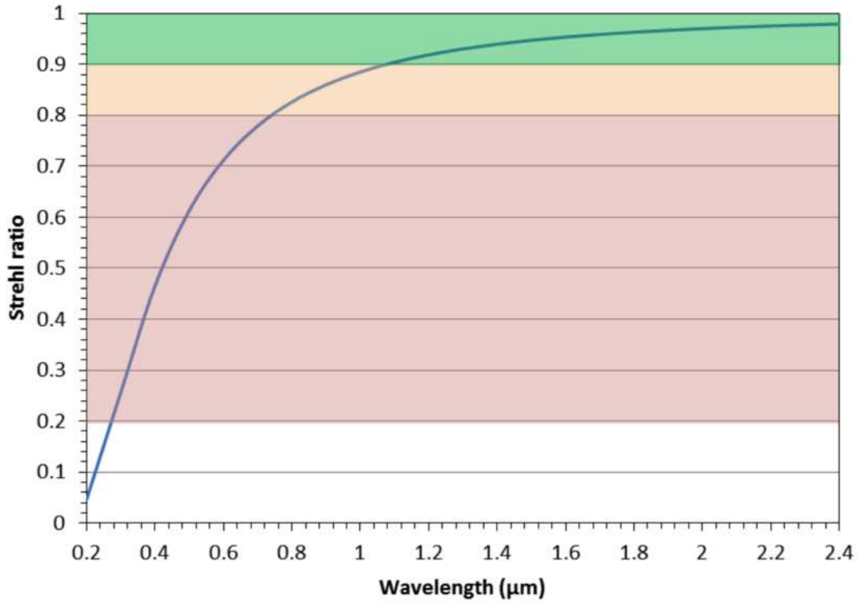

Fig. 2. Expected Strehl ratios from the wavefront correction assuming realistic WFS parameters (see text). The green region represents XAO-quality correction. No variability in throughput was explicitly considered.

Parameter	Value	Comment
Telescope diameter (m)	4.2	
r_0/500 nm	0.12	Median seeing for La Palma.
Outer scale (m)	30	
Turbulent layer altitudes (km)	0, 2.5, 4, 13.5	Layer altitudes only relevant for scintillation effects with XAO.
Relative layer strength	0.45, 0.15, 0.35, 0.1	
WFS subapertures	30 × 30	Limited by 1k DM.
WFS pixels	128 × 128	
WFS read noise (e^- RMS)	5	Read noise at 1 kHz.
WFS frame rate (Hz)	≥ 1000	
WFS FoV (arcsec)	2	Spatial filtering not included.
Guidestar/target	I-band, V=6	Equivalent to 500 photons per sub-aperture per integration.
Imaging wavelength (nm)	1650	

Table 1. Parameters for the numerical simulation of a high-order SCAO system, corresponding to the DHD configuration.

an enabler of relevant XAO technologies, as mentioned in the introduction, the DHD is able to fulfill this requirement.

3 Design and functionality of the characterisation WFS

The Characterisation Wavefront Sensor is an approximately achromatic interferometer that is designed to measure only small magnitude phase aberrations. A schematic layout is shown in figure 4 which is a modified Mach-Zhender design with one arm containing a spatial filter and a blazed grating. That arm produces a reference beam using the filter to remove the remnant high-order phase aberrations and using the grating to add an achromatic *phase* gradient across that beam [8]. When interfered with the

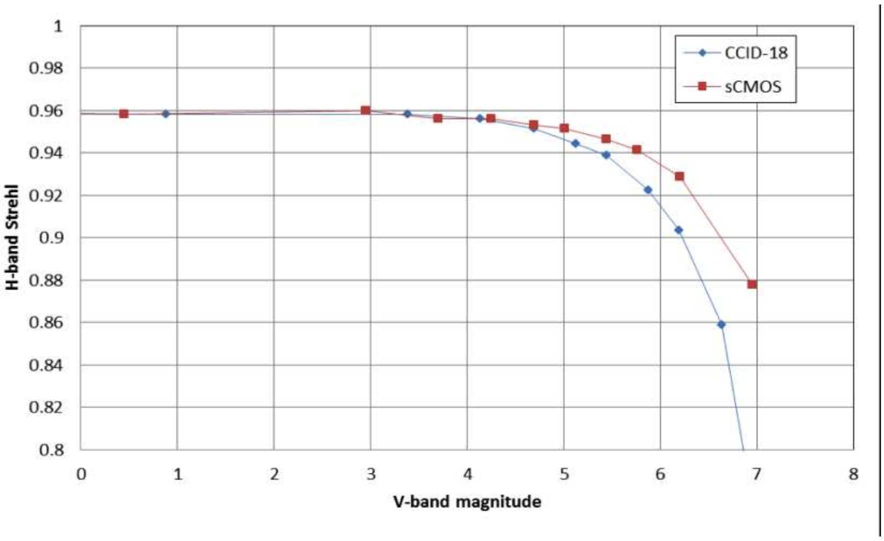

Fig. 3. The effect of varying guide-star magnitude upon Strehl ratio, for the two WFS camera choices compatible with the required frame rate of ≥ 1 kHz.

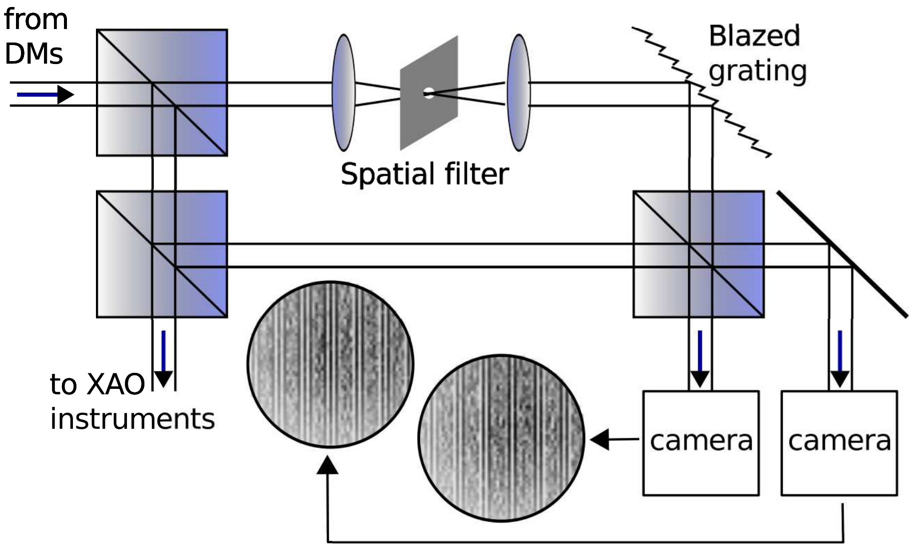

Fig. 4. An overview of one implementation of the Characterisation WFS. This design is a modified Mach-Zhender interferometer with spatial filtering and achromatic tilt in one arm.

beam from the other arm, two interference patterns are produced at the pupil plane from each port of the beamsplitter. Each imaged interference pattern consists of straight light fringes which are distorted by the aberrations; since the tilt is achromatic and the aberrations are small in amplitude (≤ 2 rad rms in closed loop) then the visibility remains relatively large. For example, using the R bandpass, to retain a visibility of 1/4 then the phase aberrations should have a RMS of 300 nm and this value is larger than predicted by the simulations.

The estimate of phase can be directly extracted using two Fourier transforms [9] which makes reconstruction particularly straightforward: in this interferometer design, the interference fringes are subtracted to remove the mean intensity; then a Fourier transform is performed on the intensity difference; the result consists of the two sidebands and one is removed by numerically setting all values except those about the chosen sideband to zero; the remaining sideband signal is shifted to the origin and an inverse Fourier transform is performed. The phase of the complex amplitude that is returned is then the estimate of phase we require, noting that if care is taken then phase unwrapping can be neglected and conversion to OPD is not difficult. This form of interferometer may therefore be described as holographic. It is also approximately 100× more sensitive than a Shack-Hartmann design, trading dynamic range for gain.

As measured, the phase measurements can be used directly in two ways. The direct application of their measurements can be fed back to the DM offsets to correct for long-term (second-long timescale) systematic errors that are one cause of quasi-static speckle that reduces the contrast ratio in post-XAO correction. The sensitivity of the CWS permits it to be used over long integrations to a high-degree of accuracy: if 0.1% of the total flux collected in R-band is diverted to the CWS (assuming no throughput losses) then over a 1 s integration to achieve 5 nm RMS error leads to a limiting magnitude of R=10. In this calculation with low-light levels it is assumed that electron-multiplying CCDs are utilised and so only Poisson noise is considered.

The second use of the CWS measurements is to characterise the correction of the AO. As an alternative to the derivation of Strehl ratio from the PSF, the CWS measurements can be utilised to estimate the flux throughput in the two arms of the interferometer. The spatially filtered arm will only transmit the coherent light that forms the core of the corrected beam PSF while the unfiltered arm will transmit all light. The *sum* of the fringe patterns are π out of phase—compare with the difference mentioned before—so the sum is the total, non-interfering intensity in each arm. The difference of the fringe patterns is the previously described interference component. By integrating each over the pupil, and calibrating a ratio of each integrated intensity (the definition is not critical here) for varying Strehl ratios, the total of the sum and the total of the difference of the two recorded fringe patterns permits estimates of the Strehl ratio.

4 Summary

The design of the Durham High-order Demonstrator is presented. This is a r_0-sampled SCAO system using NGS guide stars and is capable of diffraction-limited imaging down to the blue part of the visible spectrum. In principle, it has the capability to achieve XAO-quality Strehl ratios in the near-IR and so the DHD platform offers several capabilities: a test-bench for working with large-actuator number AO system on sky, which is ideal for testing real-time computer implementations of advanced wavefront reconstruction algorithms; a platform for high-order AO calibration and alignment especially with regards to pupil orientation/movement and the creation of large interaction matrices; a corrected beam with small residual phase errors that can be used directly or in conjunction with further coronographic and spectrographic instruments to produce a more comprehensive, on-sky test-bed that can be used to study more complex issues such as quasi-static speckle, which is one aspect of XAO that the CWS attempts to reduce.

The capabilities of the DHD as described do lend it to particular scientific targets such as: the imaging of a selected number of close AGB circum-stellar envelopes; searches for close companions; stellar binary orbit characterisation; a wide variety of solar system science; and stellar population characterisation in globular cores.

Finally, we note that an advantage of a medium-sized, 4 m telescope, is that the addition of a single sodium laser to produce one Na LGS does directly benefit a high-order AO system. For an estimated Na LGS magnitude of R=10, and accounting for focal anisoplanatism, a Strehl ratio of 0.7 is possible. Thus faint-companion searches are enabled to within 0.05” of the guide-star which need only provide a tip/tilt signal and so targets may be far fainter than a NGS-only version of DHD.

5 Acknowledgments

NAB acknowledges financial support from The Royal Commission For The Exhibition Of 1851 and valuable discussions with Gordon Love, and RM, AB, TM, and ND acknowledge Science & Technology Funding Council funding.

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