Progress with the 4m high-order AO demonstrator, CHOUGH

Nazim Ali Bharmal[a], Daniel Hölck-Santibanez[a], Alastair Basden[a], Martin Black[b], C. Marc Dubbeldam[a], David Henry[b], Timothy Morris[a], Richard Myers[a], Jürgen Schmoll[a], Noah Schwarz[b], and Edward Younger[a]

[a]Centre for Advanced Instrumentation, University of Durham, Physics, Science Laboratories, South Road, Durham DH1 3LE, UNITED KINGDOM
[b]UK Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UNITED KINGDOM

ABSTRACT

We report the progress of the Canary High-Order Upgrade (CHOUGH) addition to the CANARY AO experiment at the 4.2m WHT telescope, ORM, La Palma. While CANARY has been developed to investigate several tomographic configurations relevant to the E-ELT, it also has the ability to host guest AO instruments and provide them with relevant infrastructure. CHOUGH is a self-contained AO bench that integrates into CANARY, via an external feed of light, to provide a Strehl ≥ 0.5 in the visible. Within CANARY, CHOUGH picks off light after a 240-actuator deformable mirror and delivers the on-axis beam into the internal relay which feeds various sub-systems. These are include pick-off optics, a ADC, and 1k-actuator DM, all of which are part of an internal relay to three instruments: a spatially-filtered SH WFS, a calibration interferometer, and a narrow-field imaging camera. As CHOUGH is constructed on a separate breadboard, the components are self-contained and can be integrated and operated separately from CANARY. In this paper the progress on the design, procurement, and performance of the CHOUGH sub-systems and the experiment as a whole is given. Attention is given to the algorithms that will be used and the control methods that will be utilized on-sky. The modular nature of the design leads to potential upgrade paths and a brief discussion is made of new directions of on-sky research that could be carried out with replacement sub-systems and new instrumentation.

1. INTRODUCTION

CHOUGH is a SCAO upgrade for the CANARY AO experiment.[1] It enables a high-order 30×30, single-conjugate AO capability on a 4.2m telescope (William Herschel Telescope, Observatorio del Roque de los Muchachos). CHOUGH utilizes a Shack-Hartmann WFS together with two DMs. For analysis of AO residuals, there are two further instruments operating in the R- to I-band: a conventional imager, and a single-exposure interferometer. At present the system is between the design and procurement stages. We report here on progress

The lead group for development is Centre for Advanced Instrumentation, Durham University, who are a lead partner in the CANARY experiment. As such, CHOUGH follows a similar design philosophy to use commerical and off-the shelf components where possible to reduce cost and permit flexibility in re-configuration. (The former can aid the latter by encouraging a design which does not have large space constraints, for example.)

An overview can be seen in figure 1 which illustrates the concept of how CANARY hosts CHOUGH by feeding it with light reflected from its deformable mirror. Therefore CHOUGH "takes over" CANARY with respect to the operation of adaptive optics. In this work, we report on the progress made with the individual sub-systems and the overall integration, and using the graphical overview as a guide through CHOUGH. Comments are made on mechanical, optical, and electronic work carried out.

Send correspondence: n.a.bharmal@durham.ac.uk

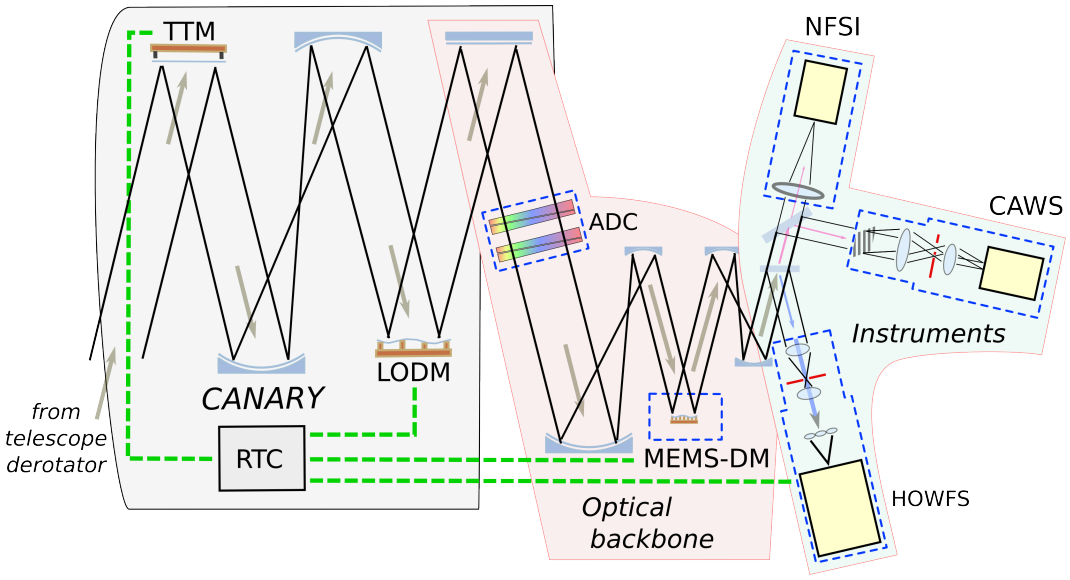

Figure 1. An overview of CHOUGH and its relation with CANARY. From left to right, (part of) the CANARY bench containing the *Tip-tilt mirror*, the *Low-order Deformable Mirror*, and the *Real-Time Computer* can be seen. Intercepting the light is CHOUGH's *optical backbone* (relay) which contains the *Atmospheric Dispersion Compensator* and *MEMS-DM* (labelled 'Kilo-DM'). The backbone relays light to three *instruments*: *High-Order Wavefront Sensor*, *Calibration and Alignment Wavefront Sensor* and, *Narrow-Field Science Imager*.

2. SUBSYSTEM DESCRIPTIONS

2.1 Use of CANARY with CHOUGH

Following a review of possible locations, the choice was made to locate CHOUGH onto a bench 430 mm above the CANARY bench following the *Low Order Deformable Mirror*–which is a ALPAO DM-241.[2] This bench placement can be seen in figure 2 which shows a rendering of a preliminary mechanical model, with the light rays within CHOUGH shown in blue together with its elevated bench.

The mirror surface of the LODM defines the pupil for CHOUGH and acts as the low-frequency high-stroke corrector in CHOUGH. Together with the MEMS-DM, the two deformable mirrors act to correct all wavefront errors up-to a spatial frequency of 27 cm^{-1} excepting tip/tilt, which is handled by the *Tip/tilt Mirror* (TTM). This choice of CHOUGH position enables a periscope to intercept the light reflected from the LODM and to bring the beam up to the CHOUGH bench. The periscope introduces a fixed-path length which then constrains the optical design of the backbone.

2.2 Optical backbone

The first two optics on the backbone, which is essentially the main optical relay of CHOUGH to the output plane that interfaces with the instruments, are the periscope mirrors. In figure 1, these are represented by the first optic in the red segment of the diagram. The *Atmospheric Dispersion Compensator* (ADC) then follows in the collimated beam. Optics then re-image the pupil onto the *MEMS-DM* and finally re-image the pupil at an output plane. Three conjugates to this latter plane, one for each *instrument*, are created to form the backbone output.

The optical design of the backbone necessitated a compact layout and use of commercial off-the shelf components where possible. Due to the narrow field of view of CHOUGH (7 arcsec) and the compact output pupil diameter (10.5 mm), it is possible to attain large focal ratio ($\sim f/30$) and this then allows spherical optics to be utilized. This reduces our need for customised optics to two pieces (one off-axis parabola and one meniscus lens). Consequently, the long f-numbers then require (fortunately only) one fold mirror to fit the backbone into the available space envelope.

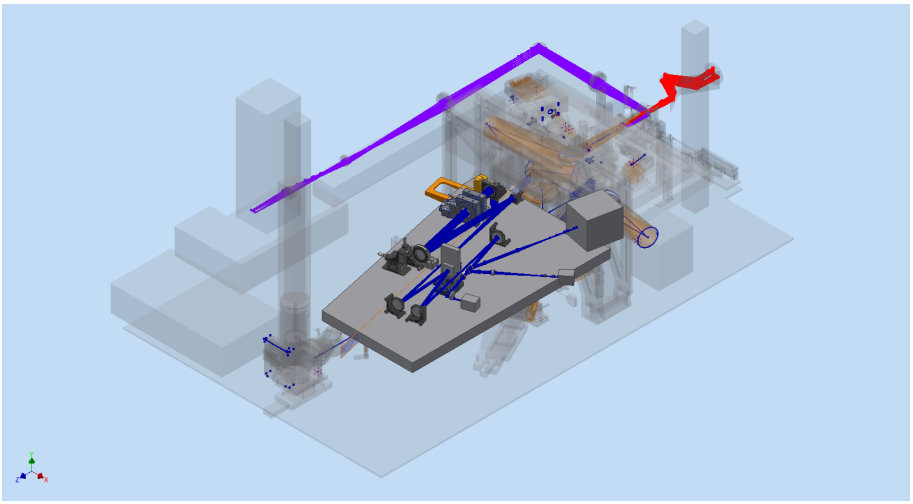

Figure 2. A rendering of the mechanical layout of the CHOUGH bench (opaque) upon the CANARY bench (translucent). The important aspect is that CHOUGH fits into the CANARY envelope at a higher level, and on its own bench. The coloured lines represent: *Purple*, the rays from on-bench CANARY alignment sources, *Red*, the rays from the telescope, and *Blue*, the rays within CHOUGH. The vertical boxes represent space envelopes for cabling. *Based on an original model produced by Tim Morris (CfAI, Durham) and Tristan Buey (Observatoire de Paris).*

2.3 Atmospheric Dispersion Compensator

The ADC is a new design and consists of a pair of Amici prisms with the design requirement of minimal *pupil shift* and operation to a Zenith angle of $\leq 60^{\circ}$. This is unusual but enables the ADC to placed at an arbitrary position within a collimated beam. Within the existing design, this is only realistic at some distance from any position conjugate to the pupil. Otherwise the design is as a normal Amici prism pair. The parameters are listed in table 1 and procurement is underway.

Table 1. The parameters describing the Amici prisms used for the CHOUGH ADC. Each plate is made up of two prisms (first and second) and two counter-rotating plates are used for the dispersion correction.

Parameter	Value (specified)
First prism glass	SBAM4
Second prism glass	STIM3
Face angles for First prisms / °	$0,\ 5.597 \pm 0.001$
Face angles for Second prisms / °	$0.0639,\ 5.597 \pm 0.001$
First/Second prism central thickness / mm	10 mm
Plate Separation / mm	30
Clear aperture diameter / mm	40

An analysis of pupil motion suggests a 0.5% maximum chromatic dispersion (relative to the pupil diameter) and an averaged 0.3% pupil shift at an observing angle of 45 degrees from zenith. A natural consequence of this limited pupil motion is that the position of the image at the focal plane is considerably shifted. For the 45°ZA, this PSF is shifted by 1.2 arcsec. Correction of the PSF shift can be achieved by offsetting the TTM based on a lookup table of ADC position.

2.4 MEMS-DM

The cornerstone of CHOUGH is the MEMS-DM that enables the high-order correction. It is a Boston Micromachines Corp. Kilo-DM with 340 µm pitch. The interface to the backbone is via an Offner relay that uses either a fixed mirror (and reflects only from sub-apertures thereof) or two independent mirrors; the choice depends

on the adaptation of the optical design to reuse an existing mirror. Currently we are characterising a new DM interface and expect the data transfer latency to be < 0.025 ms and a settling time of < 0.04 ms.

3. INSTRUMENTS

The end of the backbone is a pupil which is shared between three instruments: *High-Order Wavefront Sensor* or HOWFS, *Characterisation and Alignment Wavefront Sensor* or CAWS[3] and, *Narrow-field Science Imager* or NFSI. In principle this allows for replacement wavefront sensors or additions of alternative imagers (including coronographs), and so instrument replacement is a foreseen upgrade path for CHOUGH. In this configuration, the division of light between the HOWFS, CAWS, and NFSI instruments is that all wavelengths below 0.640 µm are transmitted to the HOWFS, while the longer wavelengths are split 90:10 between the CAWS and NFSI. The nature of the optical design precludes any analysis of polarisation so that including polarisation sensitivity in the future will not be straightforward.

3.1 High-Order Wavefront Sensor

The HOWFS is a 31×31 Shack-Hartmann wavefront sensor using 93×93 detector pixels. Each sub-aperture is configured as a quadrant cell and a one-pixel guard-band (3×3 in total). Our choice of detector is an EM-CCD camera, specifically a HNu 128×128 from NüVü Cameras of Montréal, Canada. Our choice of detector was dictated by a desire to have fast readout over the 8649 pixels, and fortunately this camera has GigE Vision connectivity. The advantage of this interface is, first, technical and, second, practical. The technical advantage is that using a customised, open-source GigE Vision library, partial pixel streaming can be achieved.[4] (It would be more accurate to describe this as partial frame streaming from the camera, but nonetheless it permits pipelining within the reconstruction stage between starting readout of WFS pixels and computing DM command vectors.) The practical advantage is that long and compact cable runs can be achieved and the software interface has no (effective) technical dependency on the operating system, which has been a previous problem for camera–computer interfacing within CANARY.[5] The expected WFS latency using our choice of detector is 0.8ms.

Before the WFS is a square spatial filter[6] which is compatible with the MEMS-DM pitch and so is available between 0.5–3 $\times \frac{\lambda f}{340\,\mu m}$. The variable f defines the focal length of the collimator. The optics that interface the input pupil to the spatial filter and then onto the lenslet array is the collimator, and then a relay specific to the camera re-images the spot array on the detector pixels. These are undergoing final design with regard to our chosen lenslet array.

3.2 Calibration and Alignment Wavefront Sensor

The CAWS is a fixed, white-light interferometer with limited phase measurement range whose use is to directly measure AO residuals. It operates by use of a Ronchi grating at a pupil conjugate, followed by a customised spatial filter that transmits only orders +1 and 0 from the grating, and ends with re-imaging the grating onto a camera. The spatial filter is designed to only transmit very low frequencies from the zero order and a limited range of frequencies from the first order: in the CHOUGH design, a 80 lpi grating is chosen which matches the sampling of the MEMS-DM and the camera is a Imperx Bobcat GEV-B0620M with $\times 4$ binning of the CCD pixels. The optics are all commercial off the shelf except for the spatial filter, whose prototype* we are characterising in the laboratory. The camera binning permits fast readout and potential to incorporate measurements of AO residuals into the control loop, but this would be demonstrated in a future upgrade. By reducing the binning, over-sampling of the fringes is possible which will allow for preventing aliasing if the wavefront residual amplitude becomes too large.

3.3 Narrow-Field Science Imager

The NFSI is a straightforward imager operating in the R- through I-bands with a field of view of 7". To accommodate the use of spherical mirrors in the backbone, a field of view compensator is utilized and this is made up of an off-centre meniscus BK7 singlet lens. The action of this lens is to remove the astigmatism introduced by the backbone, and the field then has an image quality with Strehl greater than 0.9 without use of the deformable mirrors to further compensate for static wavefront aberrations.

*From Laser Micro-machining, St Asaph, United Kingdom

3.4 Future upgrade paths

The potential to upgrade CHOUGH in the future exists by replacing one or more instruments; the available space envelope probably precludes adding a fourth instrument without a substantial optical relay. Since a WFS must be included, the possibility to install a Pyramid WFS in place of the HOWFS exists. This is appropriate with consideration of the better low-spatial frequency sensitivity exhibited by a P-WFS.

For the CAWS and NFSI, the latter could be replaced with an infra-red imager by first withdrawing the ADC and then implementing a reflective design. This would lead to a fully catoptric design for CHOUGH. With longer wavelengths In this case, the need for a supplemental wavefront sensor like the CAWS is mitigated due to reduced effects of residual, uncorrected wavefront errors. An option is then to replace both NFSI and CAWS with XAO-capable instrumentation such as a combined coronograph and imager.

4. CONTROL SYSTEM

The control system for CHOUGH will use the CANARY computer systems and the associated real-time control system.[7] An analysis of the required computational requirement demonstrates that CHOUGH requires a $\sim 8\times$ increase in raw arithmetic operations, but that the existing CPU-based processing is capable of this extra load. To accommodate mechanical limitations, the LODM will be operated at up-to 700 Hz whereas the MEMS-DM can be updated at a maximum rate of 1.1 kHz. The latter limitation is from the HOWFS. The split control of the two deformable mirrors will follow the regularised inversion of the stacked interaction matrices from each deformable mirror, with the aim of reducing the stroke on the MEMS-DM. The Kilo-DM actuators have a stroke limited to 1.5 µm while the LODM actuators have a much larger range of ≥ 25 µm. The joint aim of the reconstruction is accurate reconstruction and to prevent actuator saturation. To accommodate differential update speeds, an update-and-hold strategy will be initially employed which will maintain the LODM shape while the MEMS-DM is updated. The bandwidth for the LODM will be limited via a filter. A standard integrator will be the initially implemented control law.

For the future, the upgrade path would be to test more advanced reconstruction techniques beyond a matrix-vector multiplication towards iterative techniques (for example multi-grid[8]) and then non-matrix methods.[9] A parallel development would be to move beyond the CPU-based processing and to implement more advanced methods such as use of graphical processing units and highly-parallelized processors, specifically the Intel Xeon Phi architecture. To upgrade the control law, it is natural to consider both low-order and high-order predictive control methods based on Kálmán methods such as Linear-Quadratic Gaussian solutions (as previously demonstrated[10] with CANARY).

An important aspect of AO control is the ability to produce robust software which is able to characterise both the current and expected performance of the correction. An example of this would be point-spread function prediction, for high-contrast studies. Another example, for robustness, is automatic gain control when using an integrator.

5. SUMMARY

CHOUGH is a high-order, visible-light AO system designed for system-level experimental investigations in both instrumentation and control software. This makes it distinct from other high-order AO systems which have specific astrophysical science goals. The contrast in operation is that there are no pre-defined, specific science drivers which limit targets that can be observed, but similarly CHOUGH is a visitor instrument with significant time off-sky that permits laboratory upgrades. Consequently, a Durham–based facility to simulate CANARY will exist to allow CHOUGH to run stand-alone in the laboratory. This will both aid initial integration before CHOUGH is shipped to be integrated into CANARY, and then, contingent on additional on-sky time granted, future instrumental upgrades.

The progress of design and procurement has be described and the integration is expected to begin in Q2 2016. We welcome collaborations both for instrumental upgrades/replacements and advancements in control system design.

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