Tomography for Raven, a Multi-Object Adaptive Optics Science and Technology Demonstrator

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ABSTRACT

Multi-Object Adaptive Optics (MOAO) is an open loop approach to wide field AO which uses measurements from multiple guide stars (GS) to compute an estimate of the atmospheric turbulence in any direction within the GS asterism. Rather than trying to extend correction over the entire field as in Multi-Conjugate AO (MCAO), MOAO seeks only to generate high quality correction in specific directions with multiple deformable mirrors (DM), each driving the correction for an individual direction. A tomographic reconstructor uses the slopes sensed by the GS WFSs to estimate the atmospheric turbulence in the science directions. Raven is a MOAO science and technology demonstrator which is currently under development; testing of tomography algorithms is being carried out in order to determine the best strategy for Raven and to take the opportunity to demonstrate a range of reconstructors in simulation, in the lab and on sky.

1. MULTI-OBJECT ADAPTIVE OPTICS

Single-object adaptive optics (AO) systems are now routinely used in most major observatories to mitigate the blurring effect of the Earth's atmosphere. When imaging through turbulence, the resulting loss of angular resolution is set by the ratio of the imaging wavelength to the telescope diameter. Classical AO systems use a single wave-front sensor (WFS) and a deformable mirror (DM) driven in closed loop in real-time to measure and correct for the wave-front phase aberrations in a single direction.

The field of view of such classical AO systems is limited by anisoplanatism, which is to say, the direction in which the WFS measurements are taken (the guide star (GS) direction) is the direction in which the system has the best knowledge of the turbulence. The quality of correction in the direction of the science object drops off with angular distance from the GS as light is traveling through an increasingly different volume of atmosphere. There are currently two strategies for implementing wide field AO: Multi-Conjugate AO (MCAO), a closed loop system in which several DMs are placed in series, each conjugated to a different altitude, and Multi-Object AO (MOAO), an open loop (OL) system in which many DMs are deployed in parallel, each correcting a small field in a greater Field of Regard (FoR). The MOAO approach [1] , [2] takes advantage of the fact that we may only be interested in a few small fields spread across the FoR, as opposed to a true wide field correction. It also avoids the requirement of placing many DMs in series.

An MOAO system uses several GSs, natural and/or artificial, to probe the atmosphere across the FoR using OL WFS measurements. The information from these multiple WFSs is combined into a tomographic model of the turbulence in the volume over the telescope. If a sufficiently accurate measurement is made of the turbulence, a probe with an embedded DM can be placed anywhere in the FOR and one can compute the optimal turbulence correction for that position, which is the cumulative sum of all the turbulence in the cylinder through which the light from the science object passes during propagation through the atmosphere. The principle concepts of MOAO are illustrated in Figure 1.

2. RAVEN PROJECT

Raven is a MOAO demonstrator which will be used on-sky at the Subaru Observatory. Several OL AO systems have been successfully implemented, including ViLLaGEs [3] on the Lick 1m, VOLT [4] on the DAO 1.2m and Canary on the William Herschel 4m telescope [5]. Raven will be the first instrument to make a MOAO correction in two independent directions and feed its corrected images to a NIR imaging spectrograph on an 8 metre class telescope, an important step toward the planned Extremely Large Telescope (ELT) near IR spectrographs with ~20 deployable Integral Field Units (IFUs) over a 5 to 10 arcminute FoR assisted by MOAO such as IRMOS [6] and EAGLE [7].

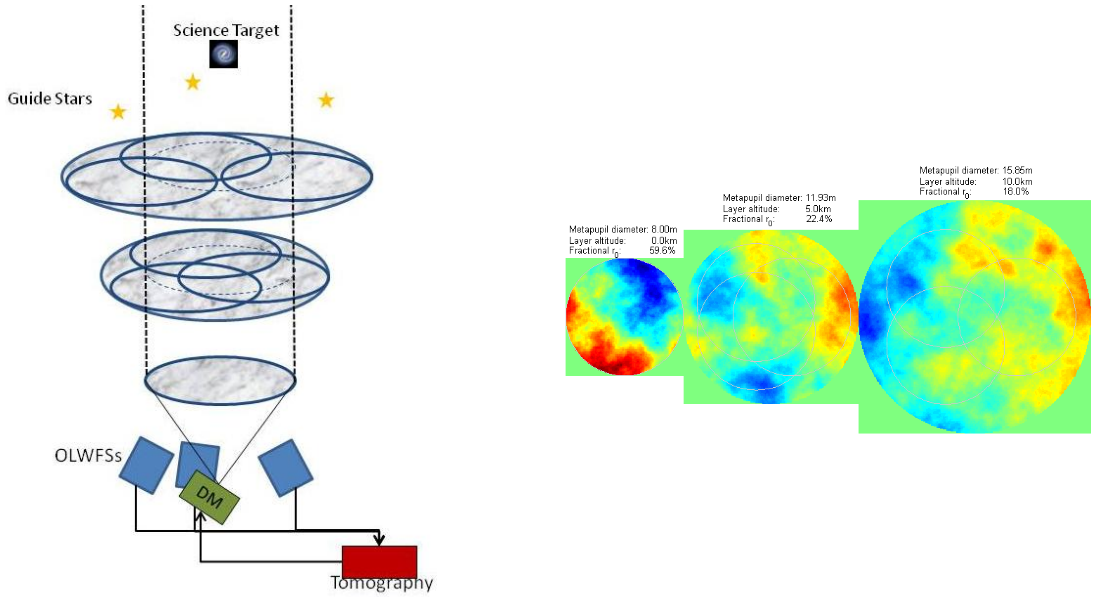

Figure 1 *left*: Several OL WFSs observe guide stars, the measurements are used to estimate the optimal DM commands to provide correction in any direction in the FoR. *Right*: The size of the metapupil increases with altitude which is why several guide stars are needed.

Raven will deploy up to three Natural Guides Star (NGS) WFSs and one on-axis Laser Guide Star (LGS) WFS (see Figure 2) to generate a tomographic reconstruction of the atmosphere in a 3.5 arcmin FoR and compute the optimal correction in two science directions. The top level requirements of Raven are listed in Table 1. It is also equipped with a calibration unit (CU), which doubles as a telescope simulator for testing and development in the laboratory. The CU simulates an 8 meter telescope with a back-illuminated pinhole grid to provide a selection of targets. The CU also simulates atmospheric turbulence with layers at ground, 5km and 10km. The upper layers are generated by rotating glass phase screens, while the ground layer is generated by a 277 actuator ALPAO DM called the calibration DM (CDM). This will allow for testing and validation of control schemes and algorithms during construction and development.

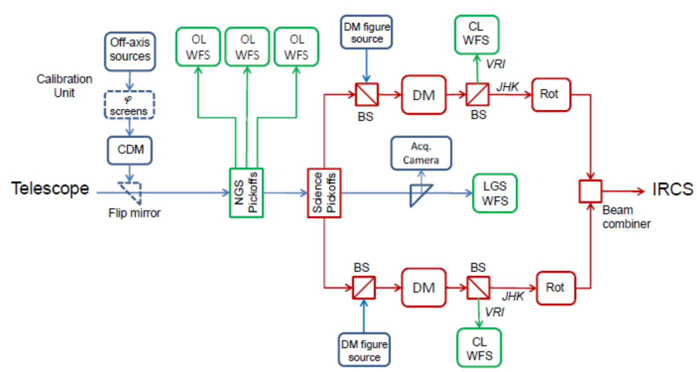

Figure 2 Block diagram of Raven’s main components: Calibration tools (blue), OL/CL WFSs and pick-offs (green) and Science paths and pick-offs (red).

Table 1 Top Level Raven Requirements

Parameter	Requirement
AO System	MOAO operation with tomographic reconstructor
Calibration System	Capable of testing MOAO during daytime and in lab
Science Instrument	Capable of feeding IRCS in imaging, grism and Echelle modes
Science spectral range	0.9-2.5 microns
# of science channels	2
# of WFS	3 NGS + 1 on-axis LGS
Field of Regard	3.5 arcminutes diameter
Science Field of View	4 arcseconds diameter per science pick-off
Delievered EE	>30% in 140mas in H-band for r_0=15 cm
Throughput	>0.32 in H-band, telescope and IRCS excluded (80% of AO188 throughput)
Image rotation	Ability to align each source to the IRCS slit
Zenith angle	<45 degrees (goal of 60 degrees)
WFS limiting magnitude	R<14 (goal of R<15)

3. TOMOGRAPHY FOR MOAO

In MOAO, the objective cost functional is the minimization of the aperture-plane residual phase variance for individual directions or over a given correction field,

$$E = \arg\min_{E'} \left\langle \left\| \phi_\beta - \hat{\phi}_\beta \right\|^2 \right\rangle \qquad (3.1)$$

In general, if a measurement can be expressed as,

$$y = x + \eta , \qquad (3.2)$$

where η is Gaussian white noise, the minimum mean square error (MMSE) estimator is given by the product of the covariance of x and y, and the inverse covariance of the observations y,

$$E = \Sigma_{(x,y)} \Sigma^{-1}_{(y,y)} \ . \qquad (3.3)$$

If measurements are made in GS directions α, the above solution can be used to estimate the phase in the aperture in the science direction β,

$$\hat{\phi}_\beta = \Sigma_{(\phi_\beta, s_\alpha)} \Sigma^{-1}_{(s_\alpha, s_\alpha)} s_\alpha \ . \qquad (3.4)$$

In practice, the measurements are WFS slopes and the estimate in the science direction can be made in any basis such as slope space, phase space, modal space, etc. A calibrated change of basis matrix is applied to the slopes. For example,

$$\hat{z}_\beta = \Sigma_{(z_\beta, z_\alpha)} \Sigma^{-1}_{(z_\alpha, z_\alpha)} Z_s s_\alpha \ , \qquad (3.5)$$

where Z_s converts slopes to Zernike space and the covariance matrices are computed for a selected number of Zernike modes. The result is an estimate of the same number of Zernike coefficients in the science direction.

3.1 Spatio-Angular Reconstructor

The motivation for using the angular reconstructor is to reduce computational complexity by computing the covariance (in any basis) in the pupil between objects separated by a given angular distance. With the angular covariance, one can then avoid computing the effects of each layer and summing them up. In modal space, specifically Zernike space, the angular covariance between any Zernike polynomials in directions α_a and α_b can be computed analytically [8], [9]starting from,

$$\langle \alpha_a, \alpha_b \rangle = 3.895 \left(\frac{D}{r_o} \right)^{\frac{5}{3}} \frac{\int_0^{h_{\max}} C_n^2(h) I_{ij}\left(\frac{\xi h}{R} \right) dh}{\int_0^{\infty} C_n^2(h) dh} , \tag{3.6}$$

where

$$\begin{aligned} I_{ij} &= (-1)^{\frac{n_1+n_2-m_1-m_2}{2}} \sqrt{(n_1+2)(n_2+1)} \times \\ &\left[K_{1,2}^{+} \int_0^{\infty} \kappa^{-\frac{14}{3}} J_{n_1+1}(2\pi\kappa) J_{n_2+1}(2\pi\kappa) J_{m_1+m_2}(2\pi\kappa x) d\kappa \right. \\ &\left. + K_{1,2}^{-} \int_0^{\infty} \kappa^{-\frac{14}{3}} J_{n_1+1}(2\pi\kappa) J_{n_2+1}(2\pi\kappa) J_{|m_1-m_2|}(2\pi\kappa x) d\kappa \right] \end{aligned} , \tag{3.7}$$

with $K_{1,2}^{+}, K_{1,2}^{-}$ coefficients that depend on m_i and n_i.

The order of the system dictates the optimal number of modes to reconstruct; Figure 3 shows the Ensquared Energy, the percentage of total incident light falling within a spectrograph slit of a given width, as a function of reconstructor radial order. The curve peaks at eleven radial orders and then drops off quickly; this is the expected result as Raven has 10x10 WFSs and 11x11 DMs. If fewer radial orders are used, many high order modes are not corrected; the high order modes are more critical than low order since the size of the spot which Raven will produce is much smaller than the width of the IRCS slit. The low order modes will blur the light over the slit, but the high orders will throw the light out of the slit. If too many radial orders are used, performance drops off due to aliasing. The results were produced using an end to end simulation of Raven built from the Object Oriented Matlab Adaptive Optics (OOMAO) library[1]

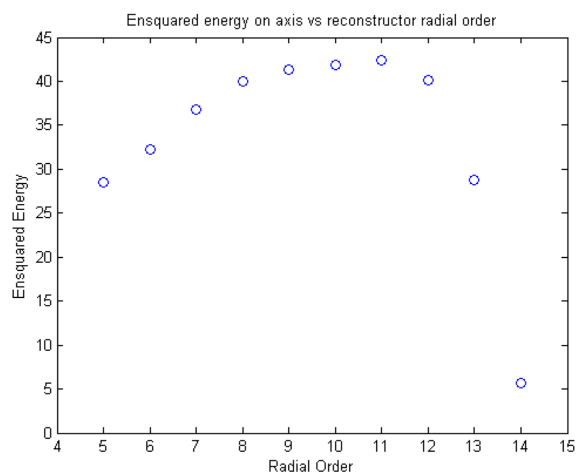

Figure 3 System performance as a function of reconstructor radial order.

3.2 Explicit Reconstructor

With this approach, a model of the atmosphere is used to compute the (system and asterism independent) covariance of a user defined number of Zernike modes within each of the layers. Each layer in the atmosphere model is defined by its wind speed, wind direction, fractional r_0, and altitude. Geometrical ray tracing operators can then be applied to obtain the covariance matrices between each of the GS directions and between each GS direction and each science direction in each of the layers. Finally the order of the system can be used to select the number of modes to estimate

[1] OOMAO is available from https://github.com/rconan/OOMAO. OOMAO was originally developed by Rodolphe Conan. Peter Hampton, Kate Jackson, and Olivier Lardière provided additional contributions.

in real time and these are extracted from the covariance matrices to build the reconstructor matrix. In theory, to eliminate spatial errors, one would compute the covariance matrix with an infinite number of modes and then select the first eleven radial orders to generate the reconstructor. In practice, the error in the first eleven radial orders becomes very small for a large but finite (several hundred) number of modes and the increase in computational complexity becomes detrimental after that.

Both the spatio-angular and explicit layer reconstructors produce the same results, and are in fact equivalent, they simply take different paths to reach the same solution. The explicit method is more computationally intensive than the angular method; however its increased complexity provides the framework to implement dynamic algorithms which work by predicting the behaviour of each layer one time step in the future. It is predicted that Raven can benefit from this type of algorithm despite the increase in computational lag time because the camera readout time is significantly longer than the time it will take to compute the DM commands using either method.

4. RESULTS WITH A SINGLE PICKOFF ARM

Raven is currently under construction at the University of Victoria; the Calibration Unit was constructed by Institut National d'Optique (INO) [10] and delivered in the first quarter of 2012. At the time of data collection, one OL-WFS pick-off arm was in place and able to patrol the FoR. The acquisition camera acts as a visual check of the pick-off arm position in the field; Figure 4 shows the pick-off arm at various positions as well as the WFS spots as they appear once the arm is centred on a pinhole source. The CU phase screens were put in place and a static shape placed on the CDM to create a static turbulence profile with a median r_0 value (~15.6cm). The OL-WFS pickoff was then moved to each of the 37 pinhole locations and the WFS slopes recorded.

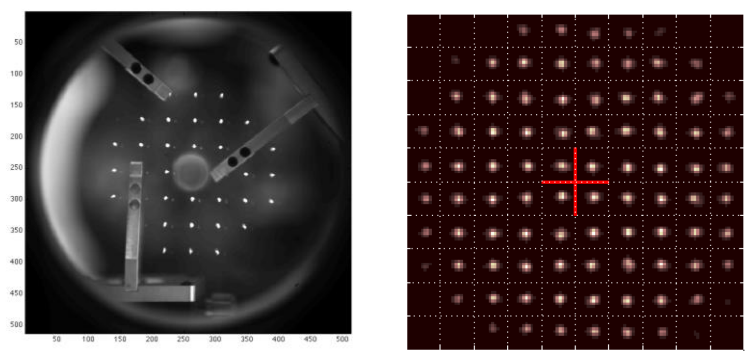

Figure 4 *left:* Stacked image of OL-WFS pickoff arm at three different positions in front of the CU pinhole grid, as seen by the Acquisition camera. *right:* OL-WFS camera image of a pinhole source (no turbulence).

With this data, any three (or four) pinhole positions could then be selected as the "guide stars" and used to estimate the slopes at any of the other pinhole positions. A direct comparison of estimated to measured values at each pinhole location could then be made. Both the explicit and the spatio-angular reconstructors in modal Zernike space were applied to the data to show that the results are in fact the same to within a percent, accountable by numerical differences accumulated in the course of matrix inversion and numerical integration.

The performance over the FoR is given by the RMS of the residual phase in nm. These values were computed for each position by projecting the estimated Zernike modes into phase space and converting the measured WFS slopes to phase for each pinhole position for a given asterism and taking the RMS of the residual phase. This was done for several asterisms with diameters of 60, 90 and 120 arcseconds. Both of the methods described in Sections 3.1 and 3.2 were applied to the same measurements; the results for the modal spatio-angular method are shown in Figure 5 and those for the explicit modal method are shown in Figure 6. Comparing both sets of results, it can be seen that the two methods give results within a percent of each other. These results represent a single frame, a snapshot of the data processing pipeline and do not include a DM in the optical path. When all three OL WFS pick-offs are operational the overall system performance can be evaluated and compared to predictions made in simulation.

5. SUMMARY AND FUTURE DIRECTIONS

This work is being undertaken with two goals in mind, the first is to achieve the best possible performance with Raven, a relatively low order system compared to planned future ELT instruments. The second goal is to explore the various approaches to tomography for MOAO keeping in mind the scale and purpose of future systems. The directions that the work will take from here are therefore to continue developing the modal reconstructor into a dynamic predictive algorithm with the purpose of improving over the static approach. Additionally, a comparative phase space algorithm is under development and appears to show improved performance over the Zernike space reconstructor. Work will continue both in simulation and using Raven with the CU as it is built.

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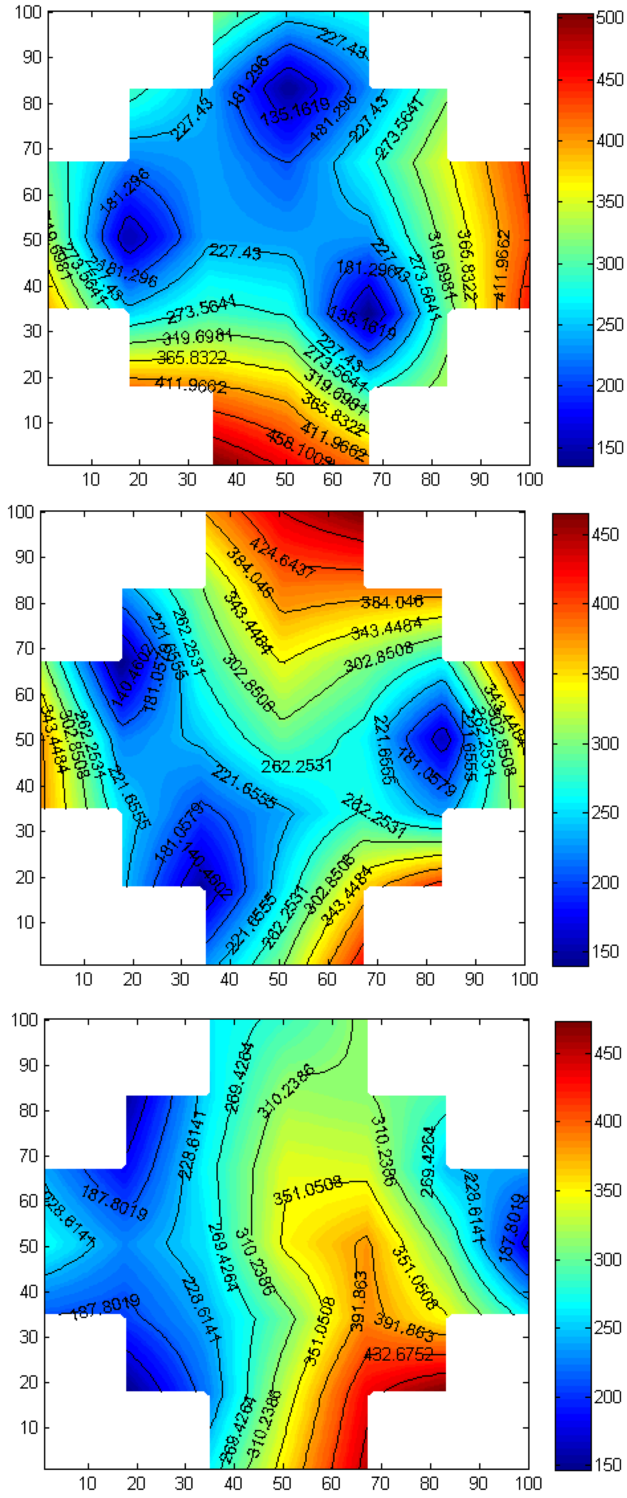

Figure 5 RMS of residual phase for the modal spatio-angular reconstructor applied to Raven WFS measurements.

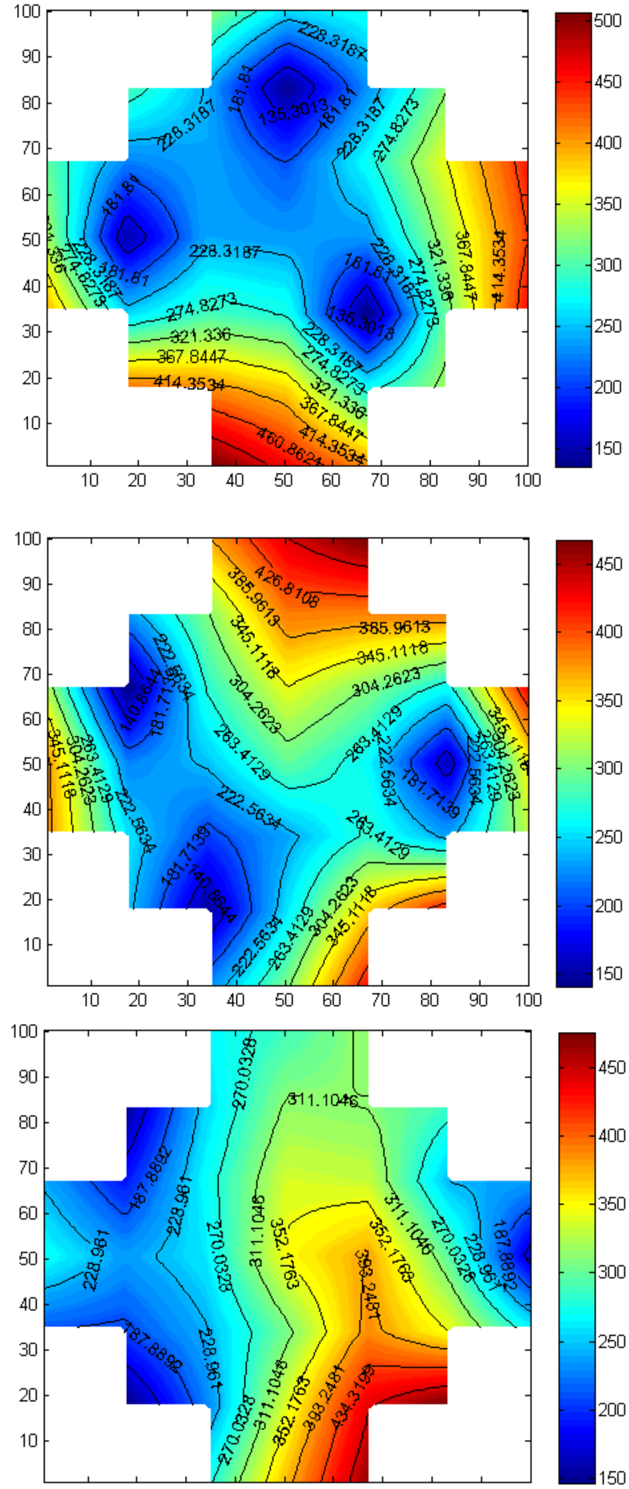

Figure 6 RMS of residual phase for the modal explicit reconstructor applied to Raven WFS measurements.