Raven Calibration

Laurie Pham[1a], Olivier Lardière[1b], and David Andersen[2c]

[1] University Of Victoria, Adaptive Optics Lab, Department Of Mechanical Engineering, 3800 Finnerty Road, Victoria, BC, V8P5C2, Canada
[2] NRC Herzberg Institute of Astrophysics, 5071 W. Saanich Rd, Victoria, BC V9E 2E7, Canada

Abstract. Multi-Object Adaptive Optics (MOAO) is an adaptive optics technique in development for Extremely Large Telescopes and will allow simultaneous observation of up to 20 targets in a several arc-minute field-of-view. Raven is an MOAO pathfinder developed by the Adaptive Optics Laboratory of the University of Victoria, in collaboration with the Herzberg Institute of Astrophysics and the Subaru Telescope. Its goal is to demonstrate that MOAO technical challenges such as open-loop control and calibration are achievable on-sky and also to deliver science results. The open-loop (OL) approach makes the need for calibration even more crucial. We will present the specific calibration procedures of Raven in two steps. The first one is to find the command matrices between the three open-loop wavefront sensors (WFS) with the two deformable mirrors (DM) used to correct the wavefront on the science paths. Because of the OL, we add components such as a calibration-DM in front of the whole system and also close-loop WFS behind each DM. We register the DM with the CL-WFS and then the calibration-DM with all of the five WFS and then compute the command matrices. The goal of the second step is to remove the field-dependent non-common path aberrations (NCPAs). That task is common in AO systems but presents a bigger challenge in this case because of the open-loop control and also the moving pick-off arms.

1 Introduction

1.1 Multi-Object Adaptive Optics

Extremely large telescope present bigger fields of view than current telescopes. These fields of view will present areas that will not need correction with adaptive optics systems because we will only study specific science cases. Hence the development of new adaptive optics methods. Multi-Object Adaptive Optics (MOAO) is one of them. It will allow simultaneous observation of up to 20 targets in a several arc-minute field-of-view. Each target uses the information of the guide stars around it to compute the wavefront associated in its direction. Each of these wavefronts is then corrected by a deformable mirror. This method of multiplexing the correcting paths works in open-loop because the DMs are located behind the wavefront sensors.

1.2 Raven : An MOAO On-Sky Demonstrator

Raven [1] is an MOAO pathfinder developed by the Adaptive Optics Laboratory of the University of Victoria, in collaboration with the Herzberg Institute of Astrophysics and the Subaru Telescope. The instrument has two science paths that will deliver on-sky data in addition to demonstrating the feasibility of an MOAO instrument for extremely large telescopes.

On the upper left corner of figure 1, there is a calibration unit. It is a telescope simulator that allows us to develop the instrument and its calibration in laboratory instead of blocking telescope time. It has sources, phase screens and a Calibration Deformable Mirror (CDM). The flip mirror is used to send the light coming either from the telescope, either from the calibration unit [2].

Then the light reaches the natural guide star pickoffs which direct the light to three open-loop wavefront sensors (OL WFS). An optional on-axis laser guide star can be used in addition to the 3 NGS or in place of one NGS.

[a] lpham@uvic.ca
[b] lardiere@uvic.ca
[c] david.andersen@nrc-cnrc.gc.ca

Two science pickoffs are used on science targets and have the same equipments on each arm. The trombones even the optical paths, the deformable mirror (DM) are used to correct the wavefront of the target and both light from the science paths are put side by side to be analysed by the Infrared Camera and Spectrograph (IRCS) from the Subaru telescope. The DM figure source and close-loop wavefront sensors (CL WFS) are key components for the calibration of the system.

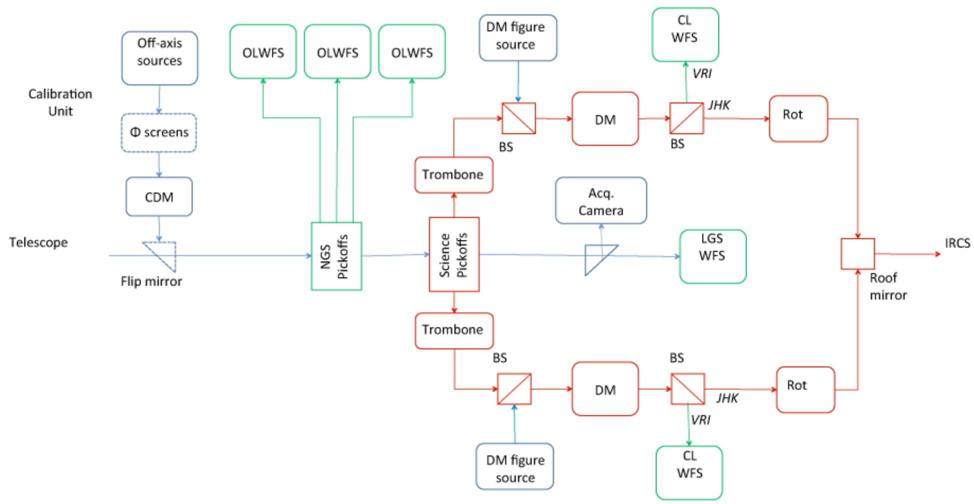

Fig. 1. Raven Schematic

2 Goal Of The Calibration

The main purpose of the calibration of Raven is to find the science deformable mirrors command matrices. Each command vector is computed as indicated in equation 1 with R, the command matrix, s the slope vector of the OL WFS, s_0 the offset slope vector of the OL WFS and c_0 the science DM reference voltages.

$$c = R(s - s_0) + c_0 \tag{1}$$

The calibration is done as much as possible in the laboratory to minimize any on-sky calibration.

3 A Proposed Method For The Raven Calibration

The fact that we cannot get the wavefront of the science object directly means that the system works in open-loop. Because of this, there is a bigger technical risk than calibrating a close-loop AO system.

The proposed method is :

- Command matrix: Calibration between the OL WFS and the science DM,
- Non-Common Path Aberrations (NCPA): Calibration of the system to remove static aberrations in non-common optical paths.

3.1 Command Matrices

The command matrix is the pseudo-inverse of the interaction matrix between the wavefront sensors and the DM. The difference in the open-loop case is that there is no direct interaction between the two devices because the DM is placed after the WFS. In order to compute the command matrices, one for each science path, we use the CDM from the calibration unit (see figure 2).

The first step is to get the traditional closed-loop interaction matrix between each DM and its corresponding CL WFS. This is done by a series of push and pull of each actuator of the science DM and by measuring the slopes on that WFS.

Then we need the relation between the OL WFS, the LGS WFS and the DM. Here, we have to use the calibration DM and the CL WFS to find the pseudo-interaction matrix between the OL WFS and the science DM. We push and pull each actuator of the CDM and measure the slopes on all the WFS (three OL WFS and two CL WFS). To collect the CL WFS slopes, we will either use the Learn and Apply [3] or a VOLT-like method [4].

Finally, we compute the command matrix between each DM and OL WFS. All these matrices are important because the rest of the calibration relies on them. We will also need the calibration matrix between the CDM and the science camera. It will be useful to close the loop between the CDM, the science camera and also for the interaction matrix between the science camera and the LGS.

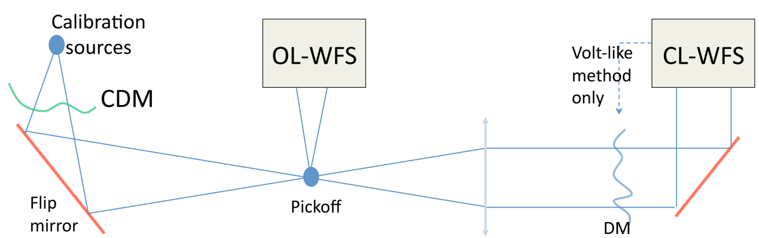

Fig. 2. Illustration of the interaction matrices computation set-up

3.2 Non Common Path Aberrations

In adaptive optics systems, static or quasi-static aberrations remain when we try to correct the wavefront on the science path using another path, the one with the wavefront sensor in it. The imperfections of the optics and misalignments need to be calibrated in order to mitigate these errors. In the case of MOAO, with moving pickoffs, those non-common path aberrations may be field-dependant, which is a big challenge because of the greater number of calibrations (or look-up tables) to be done.

3.2.1 In The Laboratory

In order to calibrate all the devices together, the deformable mirrors have to be set at a static shape. They are the reference positions that will be used during the calibration process.

Science DM reference command Equations 2 and 3 describe how we obtain the science DM reference command (DM_0). We close the loop between the DM and the CL WFS fed by the Figure Source (FS) and collect the DM voltages (reference voltages c_0). This DM shape cancels out the aberrations of science and the FS/CLWFS paths so that the wavefront measured by the CL WFS is flat (see figure 3):

$$CLWFS = f_1 + r_2 + DM_0 + f_2 = 0 \tag{2}$$

Hence, the DM reference commands are:

$$DM_0 = -f_1 - f_2 - r_2 \tag{3}$$

CDM reference command For the CDM reference command (CDM_0), we want the wavefront on the science camera to be flat so we close the loop between the CDM and a Science Camera fed by the CU sources and collect the OL WFS data for every science pick-off location. The Science camera can be a SH-WFS or a phase diversity camera.

$$Sci = u_0 + CDM_0 + r = 0 \tag{4}$$

with

$$r = r_1 + r_2 + DM_0 + r_3 \tag{5}$$

$$CDM_0 = -u_0 - r \tag{6}$$

Closing the loop between the CDM and the OL-WFS requires the interaction matrix between the OL-WFS and the CDM.

OL WFS slope offsets Then we get OL WFS slope offsets. The set-up has a Natural Guide Star (NGS) in field location #k and a science target in field location #j. It means that an OL WFS is used to sense the wavefront coming from the NGS while the science camera is set on the target. From there, we want a flat wavefront on the science camera. So the OL WFS should see the difference between the WFS path and the science path:

$$S_0 = (u_k + CDM + w) - (u_j + CDM + r) \tag{7}$$

$$S_0 = (w - r) + (u_k - u_0) - (u_j - u_0) \tag{8}$$

$$S_0 = \sigma_{OLWFS}(0) + \sigma_{OLWFS}(k) - \sigma_{OLWFS}(j) \tag{9}$$

The OL WFS slopes yield the aberrations of the CU, the OL WFS paths, the science pick-off arms and the beam combiner. The OL WFS on-axis slope offsets $\sigma_{OLWFS}(0)$ are measured when sending the reference voltages of the calibration deformable mirror CDM_0 (see eq. 10 and 11). This calibration gets the slopes of the OLWFS corresponding to a flat wavefront on the science camera when the OL WFS pickoff is located in the field of regard center.

$$\sigma_{OLWFS}(0) = u_0 + CDM_0 + w \tag{10}$$

$$\sigma_{OLWFS}(0) = w - r \tag{11}$$

OLWFS off-axis slope offsets $\sigma_{OLWFS}(k)$ measured as follows : move one OLWFS on-axis, set the current slopes as reference and scan the field of regard.

$$\sigma_{OLWFS}(k) = u_k - u_0 \tag{12}$$

CL WFS slope offsets We also have to measure the slopes of the CL WFS when the wavefront is flat on the Science Camera with the figure source or the CU central source. This calibration is required to keep the science target centred and focused in the slit of IRCS. The CL WFS can provide the tip/tilt and focus error at low rate to drive the science pick-off arm and the trombone in closed-loop. This calibration can be done for different Image Rotator positions, if it turns out that the IMR shifts the image on the slit of IRCS.

LGS WFS slope offsets To calibrate the LGS WFS slope offsets, we look for a flat WF on the science camera for a sience target in field location #j. Noting that $M_{OL/LGS}$ is the passage matrix between the OL WFS and the LGS WFS, the LGS WFS should see:

$$S_0 = u_z + w_z - (u_j + r) = (u_z + w_z - u_0 - r) - (u_j - u_0) \tag{13}$$

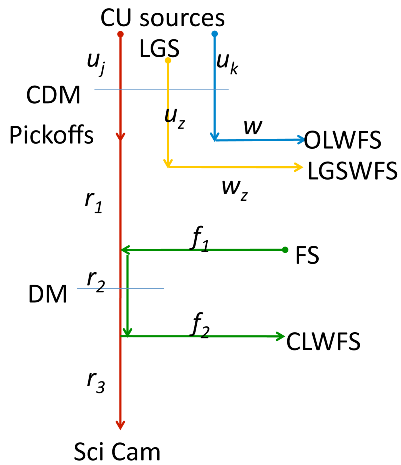

Fig. 3. Non-common path aberration measured in the lab

$$S_0 = \sigma_{LGSWFS}(z) - M_{OL/LGS}\sigma_{OLWFS}(j) \quad (14)$$

Equation 14 gives us the reference slope offsets for the LGS WFS.

The LGS WFS slopes $\sigma_{LGSWFS}(z)$ are measured with the reference command of the calibration deformable mirror CDM_0 for different zenith distances z:

$$\sigma_{LGSWFS}(z) = u_z + CDM_0 + w_z \quad (15)$$

Considering equation 6, we have:

$$\sigma_{LGSWFS}(z) = u_z + w_z - u_0 - r \quad (16)$$

3.2.2 On-Sky

The OL WFS slope offsets on-sky have the same procedure as in the laboratory with t instead of u in figure 4.

LGS-WFS slope offsets are obtained with the following equation:

$$S_0 = \sigma_{LGSWFS}(z) - M_{Sci/LGS}\sigma_{Sci} - M_{OL/LGS}\sigma_{OLWFS}(j) \quad (17)$$

where $M_{Sci/LGS}$ is the passage matrix linking the science camera on-axis wavefront measurements to the LGS WFS slopes. If the science camera measures directly the phase (phase diversity), $M_{Sci/LGS}$ may be computed from the CDM influence functions and the CDM/LGSWFS interaction matrix. $\sigma_{LGSWFS}(z)$ is the static wavefront error measured on-sky by the LG SWFS for different zenith distances and σ_{Sci} is the static on-axis wavefront error measured on-sky by the science camera.

4 Next steps

Following this calibration plan, we are currently developing :

- a model of the MOAO calibration (using ooMAO on Matlab). It currently simulates and open-loop adaptive optics system that we can compare to a closed-loop system and validate the performances of the method. Then we will add misalignment/misregistration and validate these models.
- The Calibration Unit is scheduled to be delivered to our laboratory in March of 2012. Tests on this unit will be done to validate that specifications correspond to the ones needed for Raven.

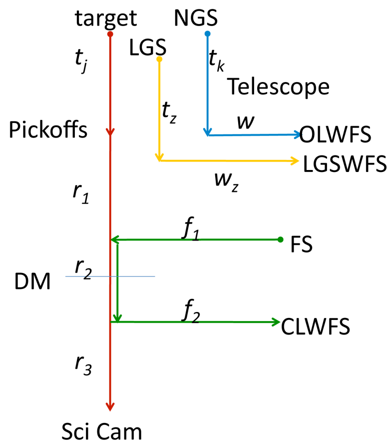

Fig. 4. Non-common path aberration measured on-sky

References

1. Raven Team, *Conceptual Design Review*, 2011
2. J-F. Lavigne et al, *Design of the calibration unit for the MOAO demonstrator Raven*, AO4ELT2 proceedings, 2012
3. F. Vidal, *Calibrations et reconstruction tomographique en optique adaptative multi-objet pour l'astronomie : Application au démonstrateur CANARY*, 2009, p.165
4. D. Andersen, *Building an Open Loop Interaction Matrix for VOLT*, OSA, 2009