Raven, a Multi-Object Adaptive Optics technology and science demonstrator

D.R. Andersen[1,a], C. Bradley[2], O. Lardière[2], C. Blain[2], D. Gamroth[2], M. Ito[2], K. Jackson[2], P. Lach[2], R. Nash[2], L. Pham[2], D. Robertson[2], J.-P. Véran[1]

[1]NRC Herzberg Institute of Astrophysics, 5071 W. Saanich Rd, Victoria, BC, CANADA
[2]AO Lab, Department of Mechanical Engineering, University of Victoria, Victoria, BC CANADA

Abstract. The University of Victoria Adaptive Optics Laboratory, the Herzberg Institute of Astrophysics and Subaru Observatory are building a Multi-Object Adaptive Optics (MOAO) technology and science demonstrator called Raven. Raven will be mounted on the Subaru NIR Nasmyth platform and will feed the IRCS imager and spectrograph. The baseline design calls for three natural guide star (NGS) wavefront sensors (WFS), one on-axis laser guide star (LGS) WFS and two science pickoff arms that will patrol a 3.5 arcminute diameter field of regard (FOR). Sky coverage is an important consideration for a science demonstrator. End-to-end simulations of Raven show that a 10x10 subaperture adaptive optics (AO) system can meet the science requirements, i.e. 30% of the energy ensquared (EE) within a 140mas slit using three R<14 NGSs, and almost 40% EE with the addition of the central LGS. We present here an overview of the Raven project.

1. Introduction

Astronomers dream of new instruments that will provide diffraction-limited images from big apertures over a large field of regard anywhere on sky. Multi-Object Adaptive Optics (MOAO) [1] is an innovative concept that can deliver on some of these dreams. On ELTs, a MOAO system with of order 20 pick-offs spread over a 5 arcminute field of regard should be able to deliver 50% ensquared energy (EE) in H-band within a 50 milli-arcsecond spaxel over 90% of the sky. With this impressive delivered performance and large mulit-plexing advantage, MOAO instruments should be work-horses on ELTs. Two science cases for which MOAO should be transformative are 1) observing large samples of “first light” objects – galaxies at redshifts greater than z>5 and 2) studying in detail galaxies during the era of peak star formation between 1<z<2.

There remain many technical challenges before the AO community can confidently proceed with building facility-class MOAO instruments for ELTs (or even 10 m class telescope). Open loop control, which is central to the MOAO concept, has only been demonstrated in the lab and on-sky for a few technical demonstrators [2,3,4]. Furthermore, calibrating a system in which the WFSs do not sense light optically downstream from the DMs is also a major

[a] e-mail : david.andersen@nrc-cnrc.gc.ca

challenge that deserves further study. MOAO also places special requirements on both WFSs and DMs; WFSs need to have large dynamic ranges and DMs need to have excellent "go-to" control. Finally, open loop tomography presents its own unique challenges in terms of both the size of the potential ELT MOAO Real-Time Computers (RTCs) and monitoring the open loop performance. Before a facility-class MOAO system is built, these risks need to be mitigated and we need to demonstrate to the astronomical community that there are tangible reasons to get support the development of facility-class MOAO instruments.

1.1. The Raven concept

The Raven project, being developed at the University of Victoria Adaptive Optics Lab, will be the first MOAO science and technical demonstrator on an 8 m class telescope. In partnership with NAOJ, we have reached an agreement that allows us to mount our visitor instrument on the NIR Nasmyth platform of Subaru. Raven will feed the IRCS [5] NIR imaging spectrograph. IRCS has both grism and Echelle spectrograph modes. IRCS contains different slits suitable for work in either seeing-limited or AO mode. We have identified the 7 arcsec by 140 mas slits as being best-suited for Raven. Raven will re-image two 4 arcsecond diameter science fields side-by-side onto the single IRCS slit. The choice to make Raven a science demonstrator that feeds IRCS has trickled down into many aspects of the design. For example, the field of regard, the number of actuators, WFSs and science pick-offs have all been chosen based on high level science requirements, as described in the next section. The overall Raven concept (Figure 1) is a reflection of these choices.

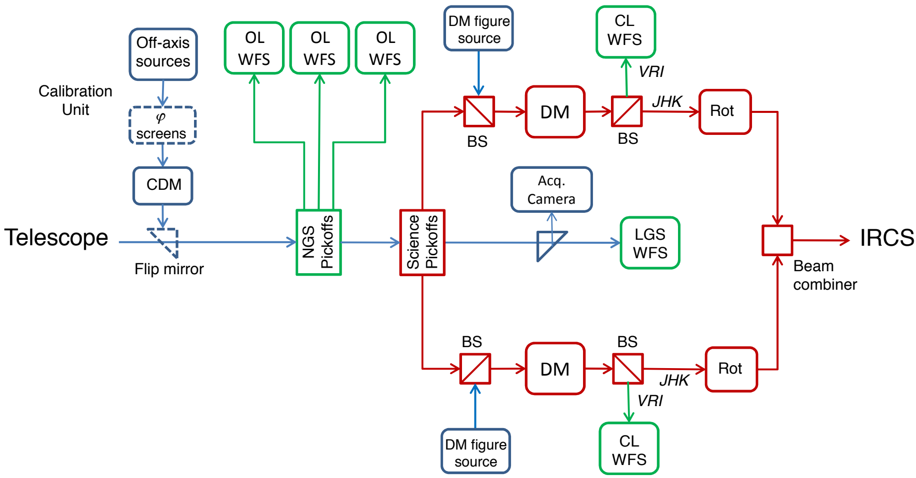

Fig. 1. Functional optical block diagram of Raven. Dashed blocks are deployable. Raven consists of 8 main subsystems: the deployable Calibration Unit, the Open-Loop NGS WFSs, the Science Pick-offs, the Science Relays, the Closed-Loop NGS Truth/Figure WFSs, the Beam Combiner, the LGS WFS, and the Acquisition Camera.

The block diagram above shows the nine major subsystems of Raven. **1)** The deployable Calibration Unit (CU) is a telescope simulator and a turbulence generator. It contains an array of off-axis NGS sources and one on-axis LGS source. Light from the CU will feed the three OL WFSs, the LGS WFS and two science arms. The three functions of the CU are to: a) help align other Raven subsystems, b) calibrate the AO system (generate interaction matrices and measure field-dependent non-common path aberrations), and c) test the MOAO system by including three phase screens (including a ground-conjugate DM inside the CU). **2)** The three NGS OL WFSs are mounted on x-y translating stages to prevent the pupil from rotating on the WFS lenslet array with respect to the DMs. **3)** Raven includes an on-axis LGS WFS which will be fed by the Subaru Sodium beacon in order to improve AO correction and/or the sky coverage. **4)** The science pick-off design consists of a mirror mounted on a r-θ arm followed by a trombone mirror that keeps the path length constant. **5)** The science relay for each arm contains a DM (which we expect to be a custom ALPAO DM with 11x11 actuators with a 25 mm aperture). **6)** A figure source and closed-loop (CL) WFS share the science relay optical path and can be used to either: a) measure the shape of the DM using the figure source, b) use the CL WFS as a truth WFS to help calibrate Raven or measure the MOAO performance, or c) use the CL WFS as a classical AO system that uses the science target as the NGS. **7)** After the science relay, light from both arms of the system are combined so that the common beam shares an identical exit pupil and provides two adjacent 4 arcsecond science fields to the single IRCS slit. The beam combiner also contains a K-mirror which can rotate the images of the science targets so that extended objects can be properly aligned onto the slits. **8)** An acquisition camera can be used to determine the telescope pointing and ensure that shadows of the probe arm fall over the NGSs and science targets. **9)** Finally, pixels from the WFS detectors will be read by the Raven RTC and transformed into a tomographic model of the atmosphere above the observatory. This tomographic model will be sampled in directions defined by the position of the science probes in the patrol field and DM commands will be generated and applied.

In this paper, we will review the top level science requirements of Raven with a mention of some of the science cases we have defined for Raven + IRCS. Then we will describe some of the key modeling results. Finally, we will describe the state of the opto-mechnical design and conclude with a brief summary that describes the future status of Raven.

2. Science Requirements

Subaru already operates AO188 [6] which can feed the IRCS NIR imaging spectrograph. We decided that Raven, as a MOAO instrument, needed to offer some multiplex advantage over AO188 for it to be successful. We translated this into a requirement on delivered EE and throughput of Raven. As a science instrument, we were also forced to make design choices that allow Raven to deliver the intended performance target even for moderately faint stars. Table 1 shows a list of the top level Raven requirements.

The first task of the Raven team was to solicit a few science cases, to help drive the opto-mechanical design. For example, a science case involving a search for extremely metal poor stars in the bulge is challenging because the Galactic bulge is never close to zenith at Subaru. Raven therefore needs to work at relatively high zenith angles, which has implications on the need for ADCs, the dynamic range of the OL WFSs, and the stroke of the DMs. A science case focusing on observing rotation curves of distant edge-on disk galaxies led us to consider the advantage of including the option of using the Subaru LGS beacon in Raven. With 1 LGS beacon, one only needs two NGSs, which therefore significantly increases the sky coverage of Raven. This helped push the field of regard of Raven to be the maximum possible FOR at the Subaru NIR Nasmyth platform (since the LGS always has to be at the field center, a ~2 arcminute diameter asterism with the LGS at one tip requires almost 4 arcminutes of field). A few science cases involved observing elongated objects. Since both science targets are re-imaged onto the single IRCS slit, we need internal image de-rotators inside Raven.

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. Modeling

Raven performance modeling played a key role in the early stages of the Raven design. Simulations were performed on two platforms: OOMAO and MAOS[7], and are described in much greater depth elsewhere [8,9]. In the course of the modeling effort, we developed an EE budget. This EE budget was derived from high order wavefront errors taken from simulations (Figure 2; including tip/tilt removed tomographic error, generalized fitting error and WFS noise) and implementation wavefront errors determined independently of simulations (including DM linearity, calibration, lag, and optical polishing errors). Including all expected errors, we expect Raven to deliver 33% EE in H-band using 3 NGS with R=14 for an r_0=15.6 cm (corresponding to the median Subaru image quality). With an additional on-axis LGS, we expect 38% EE under the same conditions

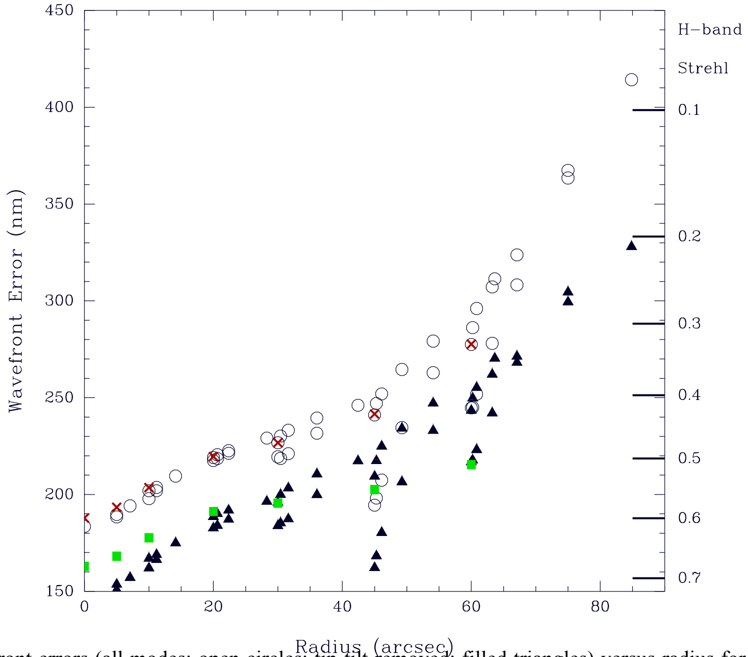

Fig. 2. Wavefront errors (all modes: open circles; tip-tilt removed: filled triangles) versus radius for field points sampling half the focal plane for 3 NGS on a 45 arcsecond radius ring and an on-axis LGS. Fractional EE (within 140 mas; filled squares) and Strehl Ratios (x's) measured from the PSFs are shown with the scale on the right (scaled to the WFEs by the Maréchal approximation. An additional ~110 nm of implementation errors are not included in this figure.

In order to achieve our requirement of delivering 30% EE in H-band even for NGSs as faint as R=14 required us to make decisions regarding the AO architecture which were not initially expected. Given budget and technical constraints, we quickly chose the Andor iXon 860 EMCCDs with 128x128 pixels. With a limited number of pixels available on the camera, we had to make compromises with regard to the OL WFS FOV, pixel scale and number of sub-apertures. We found that a fairly coarse 10x10 set of subapertures, each with 0.4 arcsec piexls and a 4.8 arcsec FOV could deliver the required performance. Large subapertures and pixel sizes have the advantage of working well even for relatively faint NGSs. Of course, performance suffers some due to the limited number of actuators, but the trade-off is acceptable. A final advantageous by-product of this choice is that alignment and registration requirements on the WFSs and DMs are relaxed.

4. Design

The Raven team is currently working on completing the final opto-mechanical design of the instrument. The design was created in Zemax and SolidWorks software, and has been designed as part of a system that includes the Subaru telescope and the IRCS NIR imaging spectrograph. The design is described in much greater detail here [10]. The layout of all the Raven subsystems (except for the CU, described below) is shown in Figure 3. Many of the optics and hardware have been ordered, and some of the parts, including an OL WFS and science pickoff, are currently being machined.

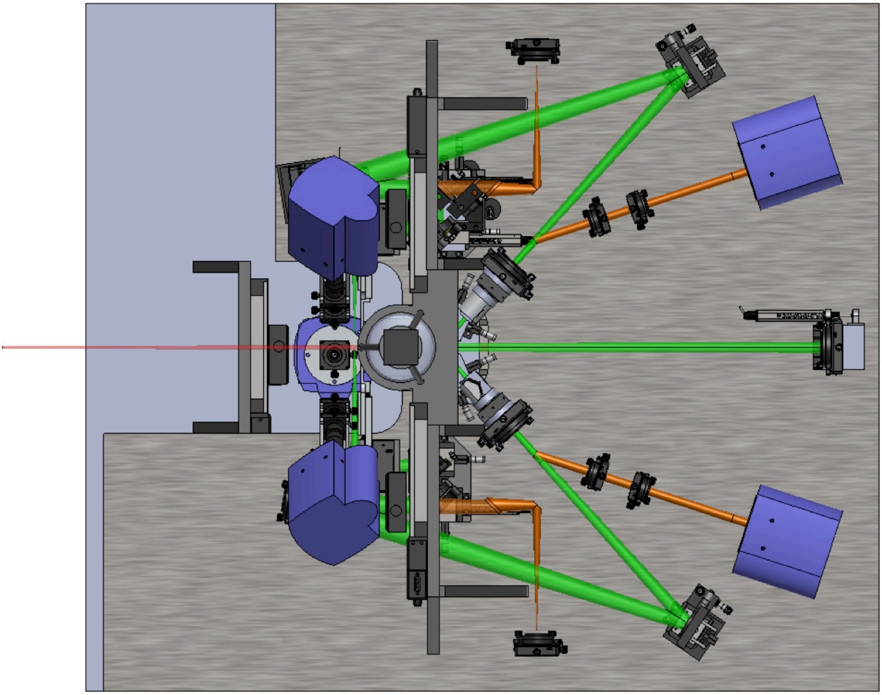

Fig. 3. Solidworks model of Raven. The 3 OL WFSs and acquistion camera are mounted on a gantry structure. The LGS WFS is located inside the bench. The science pickoffs and beam combiner (shown in green) direct the light onto he IRCS NIR imaging spectrograph.

To aid in the design effort, we have fabricated prototypes of several elements of the Raven instrument (Figure 4). We have been able to test whether the off-the-shelf stages meet the requirements on precision and accuracy when fully loaded and pulling cooling and power cables. The prototypes have also been valuable as a proving ground for our alignment plan. We are confident that the final WFSs and pick-offs will meet their opto-mechanical requirements.

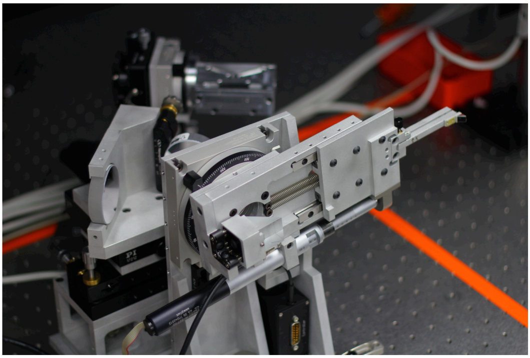

Fig. 4. Photographs of the prototype OL WFS (left) and science pick-off mechanism (right).

The Calibration Unit (CU) is a complex opto-mechanical device that is required to be a telescope plus multi-layer atmosphere simulator that delivers a large field of view. We have sub-contracted the critical piece of hardware to CU (Figure 5) to INO [11], who will deliver the CU to the UVic AO lab by the end of the first quarter of 2012. We describe how we will use the CU to calibrate and simulate Raven here [12].

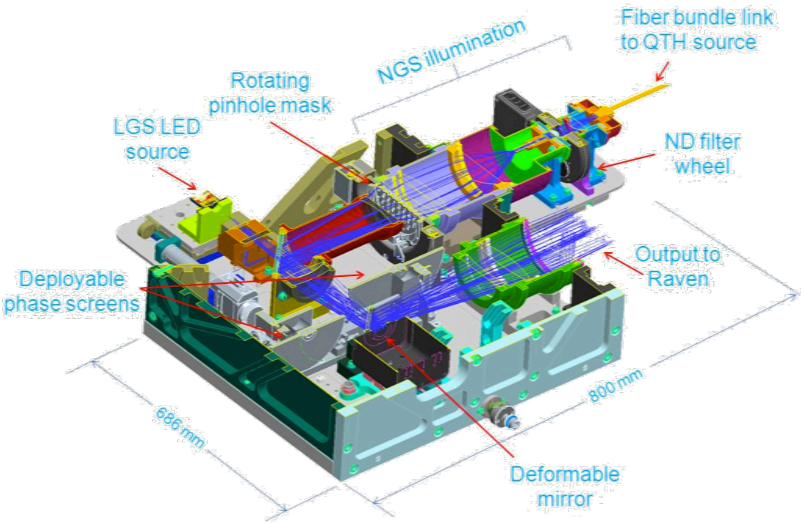

Fig. 5. Diagram of the INO Calibration Unit design. The CU will be capable of delivering simulating multiple NGS sources and an on-axis LGS source (complete with refocus to simulate different zenith distances). Two phase screens can be moved into the optical path. With these two screens that simulate high layer turbulence, a ground conjugate Calibration DM (CDM) can produce 3 layers of turbulence.

5. Summary

Raven is proceeding to a final design of all hardware and software in the first half of 2012. Many major Raven components will be delivered early this year, including the cameras, bench, CU and DMs. Several Raven subs-systems should be integrated by the end of the year. We will focus especially on the MOAO calibration challenge. MOAO operation should be possible by early 2013. Meanwhile, work is continuing on the Raven science cases. Individual science fields are being simulated, and detailed observation plans are being developed for each potential target. We will be in a position to use Raven on-sky when it reaches Subaru. Raven will be shipped to Hilo and will hopefully be mounted on the Subaru Nasmyth platform in 2014.

6. References

1. F. Hammer, et al, *Scientific Drivers for ESO Future VLT/VLTI Instrumentation,* ed. J. Bergeron, G. Monnet, 139 (2002)
2. D. Gavel, et al. SPIE, 7015, 8G (2008)
3. D.R. Andersen, et al. SPIE, 7015, 9A (2008)
4. E. Gendron, et al. A&A Letters, 529, 2 (2011)
5. A. Tokunaga, et al. SPIE, 3354, 512 (1998)
6. Y. Minowa, et al. SPIE, 7736, 122 (2010)
7. L. Wang, L. Gilles, B. Ellerbroek, *This conference*, (2012)
8. M. Ito et al., *This conference*, (2012)
9. D.R. Andersen, et al. *accepted by PASP,* (2012)
10. R. Nash et al., *This conference*, (2012)
11. F. Lavigne, et al. *This conference*, (2012)
12. L. Pham, et al. *This conference*, (2012)