Multi-Object Adaptive Optics On-sky Results with RAVEN

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ABSTRACT

Raven is a Multi–Object Adaptive Optics (MOAO) technical and science demonstrator which had its first light at the Subaru telescope on May 13–14, 2014. Raven was built and tested at the University of Victoria AO Lab before shipping to Hawai’i. Raven includes three open loop wavefront sensors (WFSs), a central laser guide star WFS, and two independent science channels feeding light to the Subaru IRCS spectrograph. Raven supports different kinds of AO correction: SCAO, open-loop GLAO and MOAO. The MOAO mode can use different tomographic reconstructors, such as Learn-&-Apply or a model-based reconstructor. This paper presents the latest results obtained in the lab, which are consistent with simulated performance, as well as preliminary on-sky results, including echelle spectra from IRCS. Ensquared energy obtained on sky in 140mas slit is 17%, 30% and 41% for GLAO, MOAO and SCAO respectively. This result confirms that MOAO can provide a level of correction in between GLAO and SCAO, in any direction of the field of regard, regardless of the science target brightness.

Keywords: Multi-Object adaptive optics, tomography, first light, Subaru Telescope, infrared spectroscopy

1. INTRODUCTION

Raven is the first Multi–Object Adaptive Optics (MOAO) science demonstrator on an 8-meter class telescope. Raven is a visitor instrument mounted on the near-infrared (NIR) Nasmyth platform of Subaru Telescope feeding the IRCS spectrograph.¹

Raven features three Natural Guide Star (NGS) and one Laser Guide Star (LGS) wavefront sensors (WFS), as well as two independent science channels. Raven has been developed at the University of Victoria (UVic) AO Lab in partnership with the National Research Council of Canada (NRC) and the National Astronomical Observatory of Japan (NAOJ).

Raven had its first light at the Subaru telescope on May 13–14, 2014. In–lab and preliminary on–sky results are presented in this paper, as well as a list of upcoming new features and expected improvements for the next runs.

2. SCIENCE REQUIREMENTS

The primary science requirements which drove the design of Raven are:

- Interface with IRCS spectrograph (λ =0.9–4.1µm, R=100–20000),
- Provide simultaneous spectroscopy:

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Two science channels within a 2-arcminute field of regard (FoR) are reimaged on IRCS slit (Fig. 1)
- 4-arcsecond field of view (FoV) per science channel
- Position angles can be selected independently

- Achieve some multiplex advantage:
  - Ensquared energy $\geq 30\%$ in 0.14-arcsecond slit
  - Throughput $\geq 64\%$ in H band

- Needs some sky coverage:
  - Two to three NGSs brighter than magnitude R=14.5 are required within 3.5-arcminute FoR.
  - Zenith angle $\leq 60^\circ$


A science team, including astronomers from Canada, Japan, France and the United States, identified several science cases with actual targets suitable for Raven. So far, the main science cases (and their PI) are:

- Finding metal-poor stars in the galactic bulge (K. Venn, M. Lamb, T. Brown),
- Brown dwarfs (Q. Konopacky),
- Star formation at galactic center (T. Do),
- Proplyds in Orion and Rosette nebulae (T. Beck, R. Mann),
- Simultaneous spectroscopy for organic molecules in protoplanetary discs and exoplanet atmospheres (H. Terada),
- Search for young/intermediate age stars in the Galactic Center region (S. Nishiyama),
- Probing globular clusters in the bulge region (M. Chiba),
- Extreme star formation and super star clusters (O. Lay, D. Gratadour, D. Rouan),
- Young star cluster candidates in the Galactic Center (T. Yoshikawa),
- Stellar population of Maffei 1 and NGC 5172 (T. Davidge),
- High redshift gravitationally lensed galaxies (K. Bandara),
- Studying high-Z QSO host galaxies (Y. Minowa),
- Kinematic galaxy asymmetries (D. Andersen),
- Kinematics of magnified galaxies in massive cluster fields (M. Ammons),
- Initial mass function in starbust clusters in the Milky Way and nearby galaxies (C. Yasui),
- Pulsating variables in nearby galaxies (N. Matsunaga).

The Raven science team is still open to new science cases and new collaborations.
Figure 1. Raven has three NGS WFS and one optional central LGS WFS. Raven can simultaneously feed the IRCS spectrograph with two distinct science targets.

3. INSTRUMENT DESIGN

The optical block-diagram of Raven is depicted in Fig. 2. A CAD model of Raven is visible on Fig. 3. A complete description of the opto–mechanical design of Raven can be found in Ref. 2. Basically, the major sub-systems of Raven are:

- The Calibration Unit (CU), built by INO,\textsuperscript{3} is a telescope simulator and turbulence generator to calibrate and test the AO system in the lab or during daytime at Subaru,

- Three Open-Loop (OL) WFSs : 10×10 sub-apertures 4.8-arcsecond FoV Shack-Hartmann using Andor iXon 860 EMCCDs,

- Two Science channels : each has a pick-off arm, a trombone, a 11×11 actuator ALPAO DM and an image rotator,

- A beam combiner to feed the IRCS slit,

- Two Closed Loop (CL) WFSs for calibration and performance comparison,

- A Figure Source to shine light on the DMs and cancel DM go-to errors,

- One on-axis LGS WFS to enhance performance and sky coverage,

- An acquisition Camera to display the whole FoV with the pickoff arms,

- A NIR Science camera for image quality assessment in the lab when we do not have access to IRCS.

It is worth noting that, due to space constraints on the Nasmyth platform of Subaru Telescope, Raven cannot use the image rotator (IMR) provided by the telescope. The use of the IMR shortens the back focus distance from 592mm to 200mm, and would prevent us from fitting the CU and pickoff arms into Raven. Consequently, the field rotation tracking is done by the pickoff arms themselves. The three NGS arms track in closed–loop, each one using its own WFS data (\textit{ie.} tip-tilt error). The two science arms can track either in closed–loop if a bright compact science target is available, or in open–loop based on the current positions of the three NGS arms.\textsuperscript{4}
Figure 2. Raven functional block-diagram.

Figure 3. Raven opto-mechanical design.
Figure 4. Expected turbulence profile generated by the DM (ground-layer) and the two spinning phase screens (5.5 & 10.5 km) of the Calibration Unit, compared to the measured profile from the WFS slopes covariance matrices (SLODAR). The measured value of \( r_0 \) is likely more correct than the nominal value, as the calibration DM and phase screens cannot reproduce the highest spatial frequencies.

Figure 5. Science camera images, ensquared energy (EE) and Strehl ratios (SR) or FWHM achieved during daytime with the Calibration Unit in J-band. EE is computed in 140mas, the width of IRCS slit. NGS asterism is 2–arcminute wide, NGS R magnitudes are 11.5, 12.1 and 12.1. The camera frame rate is 250Hz.
4. LABORATORY RESULTS

The CU of Raven can be used in the laboratory or during daytime at the telescope to calibrate the system and test the different AO modes.

Raven is an AO system able to operate in classic single–conjugated closed-loop AO (SCAO) using the CL-WFSs on a bright science target, in open-loop ground-layer AO (GLAO) by averaging slopes from the three or four guide star WFSs, and in multi-object AO (MOAO) by computing the best correction in the science direction using the signal from multiple open-loop WFSs and a tomographic model of the atmosphere.

The tomographic reconstructor used for MOAO is based on a model of the atmospheric turbulence. In practice, the model needs to know the position of all NGSs and science direction, as well as the current Fried parameter, outer scale, \( C^2_n \) profile, and optionally the wind profile. \(^5,6\) These atmospheric parameters are computed on-the-fly from the data of the OL-WFS acquired during AO corrections (Fig. 4). This technique is known as SLODAR.\(^7,8\)

Alternatively, Raven can use the Learn&Apply reconstructor (L&A), developed by the CANARY group.\(^9\) This tomographic approach does not need any prior knowledge or assumption about the atmospheric conditions, but requires a bright and compact science target to measure the wavefront in the science direction. On bright NGSs, we usually get better performance with the L&A than with the model-based reconstructor. Nonetheless, the L&A is not the baseline reconstructor for Raven, because, as a science demonstrator, Raven must work regardless of the brightness or size of the science target.

Figure 5 displays the images obtained for one science channel on the science camera for the different AO modes listed above (except L&A), with and without the on-axis LGS. This level of performance are in good agreement with the simulations including implementation errors\(^10\) and meet the science requirements.

5. ON-SKY RESULTS

In this section, we present the very first results of Raven obtained on the sky with Subaru telescope and IRCS spectrograph on May 13 and 14, 2014 (Fig. 6). Four more nights are scheduled in August 2014.

5.1 AO results on engineering fields

A dozen engineering fields featuring at least 5 stars brighter than R=14 within 3 arcminutes field of view have been identified for this first run.

5.1.1 NGSs and science target acquisition

The Raven acquisition camera imaged the accessible FoR and helped enable rapid acquisition of the 3 NGSs and 2 science targets. In most cases, we were able to acquire slopes on the WFSs within 5 minutes of the end of the telescope slew. On the user interface, circles are automatically drawn on top of the acquisition camera image to show where the NGS and science targets are expected to be. Then, the user simply click on the actual position of stars to move the pickoff arms.

Once the NGS spots appears in the WFS subaperture, the pickoff arm tracks the NGS in closed loop to compensate the field rotation. The science pickoff arms can track either in closed-loop if the science target is bright and compact, or in open loop based on the NGS pickoff arms positions.

5.1.2 AO performance

Figure 7 shows an engineering field observed by Raven on May 14, 2014 with the actual positions of the WFS and science target pickoff arms when the observation started. The images of the two science targets, located 40 arcsecond apart on the sky, are displayed in Fig. 8 for different AO modes: No AO, GLAO, MOAO and SCAO. The two science channels are reimaged side-by-side, 2.25 arcseconds apart, to fit comfortably in IRCS spectrograph slit. The ensquared energy (EE) within 140mas is computed for each AO modes.

The images obtained with no AO correction are not symmetric because the exposure time was roughly 20 seconds – not long enough to average out all the turbulence. GLAO offers a substantial image quality
Figure 6. (a) Raven installed at the Nasmith focus of Subaru Telescope next to the IRCS spectrograph (the grey box). (b) The Raven team in the control room awaiting the very first light of the instrument on May 13, 2014.

Figure 7. (a) Digital Sky Survey image of the engineering field #38 (RA=15h15m32.16s, DEC=+05°16’31.2”) used for Raven first light with the actual position of the pick-off arms. (b) The 2 science targets are 40 arcseconds apart on sky and are reimaged side-by-side on the infrared science camera of Raven (broadband image: $\lambda = 1.0 - 1.7 \mu m$). The dotted squares shows the portion of the image enlarged in Fig. 8. The R magnitudes of the three NGSs and two science targets are respectively 10.2, 12.4, 12.8, 10.9 and 12.5.

improvement over a very wide field of view, but MOAO offers an even better correction on any direction, regardless of the brightness of the science target.

Table 1 summarizes and compares the results in terms of EE. This table shows that the preliminary results obtained on the sky are pretty close to the one obtained in the laboratory. Simulations made specifically for this engineering field, including implementation errors,\textsuperscript{10} also match the on-sky results within 5% of EE for the L&A MOAO reconstructor. These preliminary results are encouraging, because we know that the performance can still be improved in the near future (Sec. 6).
Figure 8. Close-up of the images obtained on field #38 (Fig. 7) for both science channels with different AO corrections. The frame rate of all NGS WFS camera is 100Hz. Broadband image ($\lambda = 1.0 - 1.7\,\mu m$) acquired with the science camera of Raven. Ensquared energy (EE) is computed for a 140mas wide slit. Total exposure time is 20s for each case. The images have been scaled to their maximum intensity, independently for both channels. Intensity values are for channel #2.
Table 1. Percents of the total energy ensquared (EE) within 140mas obtained on sky, in the laboratory and from simulation. On-sky EE is computed from images obtained on engineering field#38 (Fig. 8) with AO loop running at 100Hz and \( r_o = 23.4 \text{cm} \). In-laboratory EE is computed from images obtained during daytime with the Calibration Unit (Fig. 5) with \( r_o = 22 \text{cm} \), AO loop running at 250Hz on an asterism of similar magnitudes and diameter (2') but with science targets very close to the center (same performance for both channels). Simulation is for field#38 at 1.3\( \mu \text{m} \) with AO loop running at 125Hz and \( r_o = 23.4 \text{cm} \). As MOAO simulation does not include modelization error, simulated performance should be compared to results obtained with the Learn&Apply reconstructor.

<table>
<thead>
<tr>
<th>AO mode</th>
<th>On-sky</th>
<th>In-lab</th>
<th>Simulation</th>
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<tbody>
<tr>
<td></td>
<td>ch#1</td>
<td>ch#2</td>
<td>both ch.</td>
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<tr>
<td>no AO</td>
<td>13.1</td>
<td>12.0</td>
<td>9.7</td>
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<tr>
<td>GLAO</td>
<td>15.6</td>
<td>17.0</td>
<td>17.9</td>
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<tr>
<td>Model-based MOAO</td>
<td>22.9</td>
<td>25.0</td>
<td>29.0</td>
</tr>
<tr>
<td>Learn&amp;Apply MOAO</td>
<td>32.2</td>
<td>41.0</td>
<td>44.8</td>
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<tr>
<td>SCAO</td>
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Figure 9. Turbulence profile and \( r_o \) measured on-the-fly with Raven WFS (SLODAR) during AO corrections shown in Fig. 8. The profile is compared to CFHT MASS data taken at same time (Ground-layer turbulence is not sensed by MASS instrument).

5.1.3 SLODAR profiles

Figure 9 plots the turbulence profile from 0 to 12km measured on the fly with the NGS WFS data (SLODAR). Our SLODAR profile is compared to the CFHT MASS profile taken at same time. There is a fairly good agreement between both profiles, knowing that the MASS instrument only senses turbulence at fixed altitudes (0.5, 1, 2, 4, 8 and 16km), is not sensitive to ground layer and it was not pointing the same direction as Raven. Also, our SLODAR technique tends to overestimate the turbulence seen in the highest altitude bin used for the best fit (12km here). The same \( r_o \) is measured by Raven WFSs and the CFHT DIMM (0.234 and 0.246m respectively), suggesting dome seeing within Subaru was minimal at that time.

5.2 Results on Saturn with IRCS Imaging mode

Figure 10 displays the images obtained from Saturn on night May 14, 2014 with the IRCS imaging camera. Three moons of Saturn (Tethys, Dione and Rhea) were used as NGSs, while two areas of Saturn’s rings, located
Figure 10. Images of Saturn taken with the Raven MOAO demonstrator at the Subaru telescope. Three moons of Saturn have been used as NGS. Two distinct areas of Saturn rings and clouds, located 30 arcsec. apart, have been imaged on IRCS camera (imaging mode) with no correction and with MOAO correction. Three exposures using different filters have been combined to produce these coloured images (Red: 1 sec. in K', Green: 0.4 sec. in H, Blue: 0.4 sec. in J).

30 arcseconds apart, were used as science targets. MOAO is particularly interesting in that case, as the lack of compact science targets makes conventional closed-loop AO nearly impossible.

Saturn is a challenging case for Raven, because the shape of “NGS” asterism changes with time due to orbital motions of each moon. This makes the open-loop tracking of the science arms more difficult and causes a slow drift of the science target. Fortunately, only short exposures are required for Saturn. The seeing was 0.35 arcseconds without correction, 0.1 arcseconds with MOAO correction.

5.3 Science validation with IRCS Echelle mode

Figure 11 presents the echelle spectra obtained with IRCS spectrograph. The science targets are two Red-Giant-Branch stars located in the globular cluster M71. These spectra are the first astrophysical results ever obtained with a MOAO instrument.

These two stars are standard stars for the Galactic Centre science case. Our analysis of them should provide the same results as others have published so that we can be sure there are no systematic errors (observational or modelling) in the main science targets which have never been examined.

The echelle spectra obtained with Raven are comparable to the spectra of the same star taken two years ago with AO188.11

In infrared spectroscopy, the variability of sky emission is corrected by nodding the target along the slit from point A to point B, usually with an ABBA cycle. Ideally, each integration should not be longer than a couple of minutes. In the case of Raven, the nodding is done by offsetting the positions of the probe arms, while they are tracking the field rotation and the MOAO loops are running. The A and B positions of each channel must be carefully determined to avoid putting the science targets in positions where the spectral orders overlap. Ideally, the distance between the two targets should be half the distance between two consecutive orders.
Figure 11. First spectra obtained from a MOAO instrument. The science targets are two Red-Giant-Branch standard stars located in globular cluster M71. Both stars, located 30 arcsecond apart on the sky, are reimaged side-by-side to fit in the slit of IRCS spectrograph. The spectrum obtained with Raven channel #2 (blue) is compared to a spectrum of the same star taken two years ago with AO188 (light gray). Only the first 7 orders have been plotted. H-band echelle mode, spectral resolution R= 20000, total exposure: 180s.
6. FUTURE WORK

The on-sky results presented here are preliminary. We are still processing the data collected during the first run in order to fully characterize the performance of the system and try to improve them for the next engineering run scheduled in August 2014. This section lists possible actions to improve the system.

6.1 Vibration analysis

Sometimes, the on-sky images were elongated in one direction. A preliminary analysis of the WFS slopes shows the presence of a 5Hz vibration with a peak-to-valley amplitude of 0.4 arcsecond. The direction of the vibration looks consistent with the 5-6Hz Elevation vibration of the telescope. The vibration amplitude is also consistent with the elongation of stellar images due to telescope vibration.\(^{12}\)

A detailed analysis of all the NGS WFS slopes is still needed to determine vibration occurrence over the night and compare with telescope position and wind speed measurements. If it turns out that the cause of the vibration is the telescope, we will have to avoid the “shaky” spots of the telescope and/or try to implement a vibration mitigation in the AO controller of Raven.\(^{13}\)

6.2 Canceling quasi-static and field-dependent aberrations

During the first engineering run, no efforts have been made to cancel the static field-dependent aberrations of the telescope. This would require long time-averaging of the NGS WFS slopes – to average out the turbulence – for different locations in the field and then apply a slope offset on each WFS. This task has been judged too time-consuming for the first run, so we decided to focus on other aspects of MOAO. However, an analysis of all the slopes collected during the first run is in process in order to map the aberrations of the telescope in the FoR. From these data, we will attempt to cancel the field-dependent aberrations of the telescope for the next run in August.

Another source of static error is the slow drift of the DM best flat. The best flat of the ALPOA DM used in Raven is known to drift in focus when the temperature changes. In the laboratory, it is quick and easy to update the best flat command by closing the loop with the CL-WFS. During on-sky observation, we are planning to shine the Figure Source (FS) of Raven on the DM and re-flatten it using the CL-WFS periodically in closed–loop.

Non-common path aberrations (NCPA) were minimal between Raven and the IRCS imager. Nonetheless, we are planning to implement a focal plane sharpening algorithm\(^{14}\) using IRCS images, as a backup solution if NCPA arise in the future.

6.3 Outer scale

For the first run of Raven, we did not estimate the outer scale. For the model-based MOAO reconstructor, we assumed the outer scale was 30 m. However, the outer scale can have significant impacts on AO performance, so for the next run, the outer scale will be estimated by fitting the auto-correlation peak of the slopes of each NGS WFSs.\(^{15,16}\)

6.4 Predictive reconstructors and wind profiler

A static tomographic reconstructor has been tested on-sky. However, in the laboratory, we have tested predictive algorithms such as a ”Lead-Off” spatio-angular reconstructor and a LQG.\(^{5,6}\) According to their performance in the lab, the frame rate of the WFS could be reduced to 40Hz with no penalty. These should increase the NGS limit magnitude of Raven by 2 magnitudes. These predictive controllers need both the wind speeds and directions of all turbulent layers. A wind profiler is going to be implemented in the system, using an algorithm similar to the one developed for Canary.\(^{16}\)
6.5 Advanced centroiding algorithms

The centroiding algorithm used so far to compute the wavefront slopes from the WFS images is the conventional threshold center-of-gravity (CoG), the threshold being defined as a fraction of the maximum intensity in each subaperture. The correlation algorithm is less sensitive to noise and could provide a gain of +1 magnitude for the NGSs.

An improved version of the correlation algorithm has been developed for open-loop AO\(^{17}\) and implemented in the Raven real-time computer (RTC) but tested only in the laboratory. As the correlation is computationally more intense than the CoG, the frame rate of the WFS cameras has to be reduced to 150Hz. This speed limitation is actually not an issue for two reasons: (i) the correlation is most beneficial for faint stars, so the frame rate has to be reduced anyway to collect enough photons, (ii) the lag error can be mitigated by a predictive reconstrutor (Sec. 6.4).

The correlation should improve performance on the elongated and noisy LGS spots too. The laser of Subaru was used a few times during the first run of Raven. We successfully acquired, centered, focused and tracked the LGS spots with the Raven LGS WFS. However, the use of the LGS did not significantly improve the AO performance with the CoG because the LGS were quite faint (mag. = 13) and elongated.\(^{17}\)

For the next run, we will use the CoG only for very bright stars (R\(\geq\)11) up to 500Hz, and use the correlation centroiding algorithm with the LGS and fainter NGS stars with frame rates up to 150 Hz.

6.6 Science target tracking

As Raven cannot use the image rotator of the telescope, each pick-off arm has to track the field rotation (Sec. 3). The arm tracking worked pretty well since the first night, but its performance could be improved in two specific cases, (i) when the science arms track in closed-loop with SCAO engaged, (ii) when NGS are faint and the science pickoff arms track in open-loop (using NGS arms positions).

In the first case, there is a conflict between two closed loops, the SCAO loop and the science arm tracking. To avoid this conflict, an offload of the DM command to the science arm stages will be implemented.

In the second case, the noise coming from the NGS tip/tilt propagates into the science arm tracking, causing wobbles on the science target. To improve the open-loop science target tracking, we are going to track a precomputed position (based on telescope coordinates and time), and lower the gain and/or frequency of the feedback coming from NGSs pick-off arms.

7. CONCLUSION

Raven is a MOAO science demonstrator which successfully got its first light on Subaru Telescope in May 2014. Raven is the first MOAO instrument capable to feed a science instrument (IRCS spectrograph) and to correct simultaneously the turbulence for two independent science channels. The spectra presented here are the first useful astronomical data obtained with MOAO.

The preliminary results of Raven confirmed that MOAO provides a correction level in between GLAO and SCAO, in any direction of the field, regardless of the brightness or the size of the science target.

A second observation run is scheduled in August 2014 including three more engineering nights and one science night. Hopefully, more science nights will be allocated to Raven in 2015 through the Subaru Open Use Normal Program (science proposals made by the PIs of each science case).

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