Title

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On-sky results of Raven, a MOAO science demonstrator at Subaru Telescope

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ABSTRACT

Raven is a Multi-Object Adaptive Optics science demonstrator which has been used on-sky at Subaru telescope from May 2014 to July 2015. Raven has been developed at the University of Victoria AO Lab, in partnership with NRC, NAOJ and Tohoku University. Raven includes three open loop WFSs, a central laser guide star WFS, and two science pick-off arms feeding light to the Subaru IRCS spectrograph. Raven supports different AO modes: SCAO, open-loop GLAO and MOAO. This paper gives an overview of the instrument design, compares the on-sky performance of the different AO modes and presents some of the science results achieved with MOAO.

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] The main goal of Raven is to get first science results from MOAO and to prepare the future MOAO instrumentation for ELTs.

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 is a fast-track project founded by the Canadian Fund for Innovation (CFI grant) with a conceptual design study started in March 2011. Raven had its first light at the Subaru telescope on May 13–14, 2014, with additional runs on August 6–10, 2014 and from June 23 to July 1, 2015.

In total Raven got 12 clear nights, which have been shared between engineering (7.5 nights) and science time (4.5 nights). About half of the engineering time was devoted for commissioning Raven, as a science instrument (acquisition, throughput, plate scale, tracking, nodding, etc.), and the rest of the time was for pure AO engineering. This paper gives an overview of the instrument design and presents AO engineering and science results obtained on the sky with MOAO correction.

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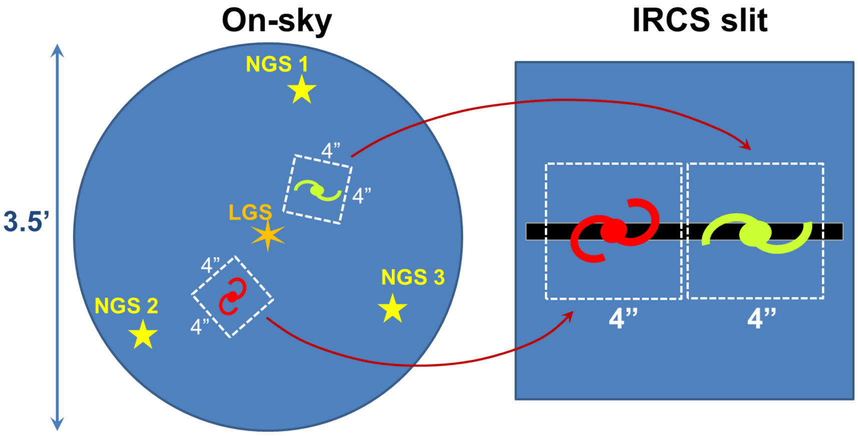


Figure 1. Raven has three NGS WFS and one optional central LGS WFS. Raven can simultaneously feed the IRCS spectrograph with two distinct science targets.

2. SCIENCE REQUIREMENTS

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

- Interface with Subaru and IRCS spectrograph (F/13.6 beam, $\lambda = 0.9$–4.1μm, R=100–20000),
- Provide simultaneous spectroscopy:
  - 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
  - Dithering and ABBA nodding for background subtraction
- 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 are required within 3.5-arcminute FoR.
  - Make use of Subaru on-axis LGS
  - Zenith angle $\leq 60^o$
- Supported AO modes: MOAO, open–loop Ground–Layer AO (GLAO), closed–loop Single–Conjugated AO (SCAO).

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,[3] is a telescope simulator and turbulence generator to calibrate and test the AO system in the lab or during daytime at Subaru,

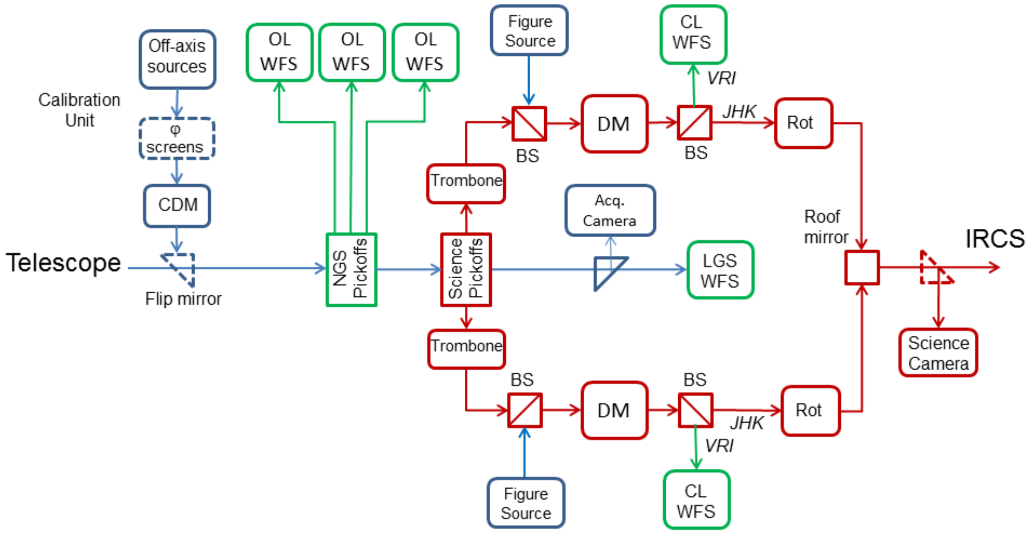


Figure 2. Raven functional block-diagram.

- 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 (Fig. 5),
- A NIR Science camera for image quality assessment in the lab or when we do not have access to IRCS.

The relatively small number of actuators across the pupil (10×10) was a trade-off meeting both the sky coverage and the image quality requirements. It is worth noting that 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 Raven would not fit between the telescope elevation bearing wall and the Nasmyth focus (Fig. 4). Consequently, the tracking of the field rotation is done by the pickoff arms themselves. The three NGS arms track in closed–loop, each using its own WFS data (*i.e.* tip-tilt error). The two science arms 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.[4]

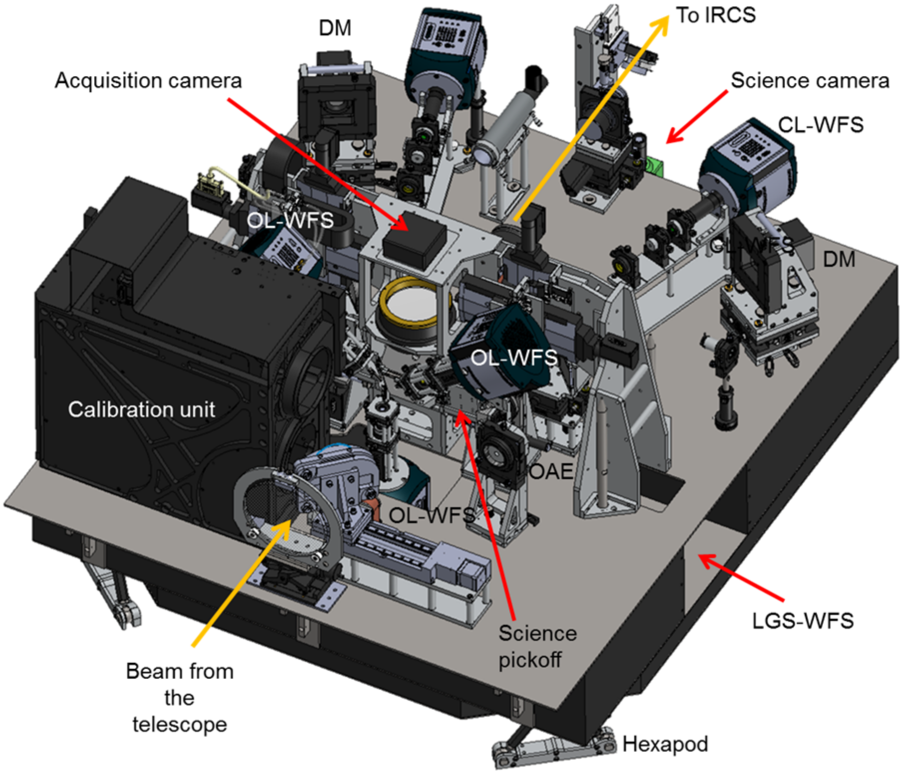
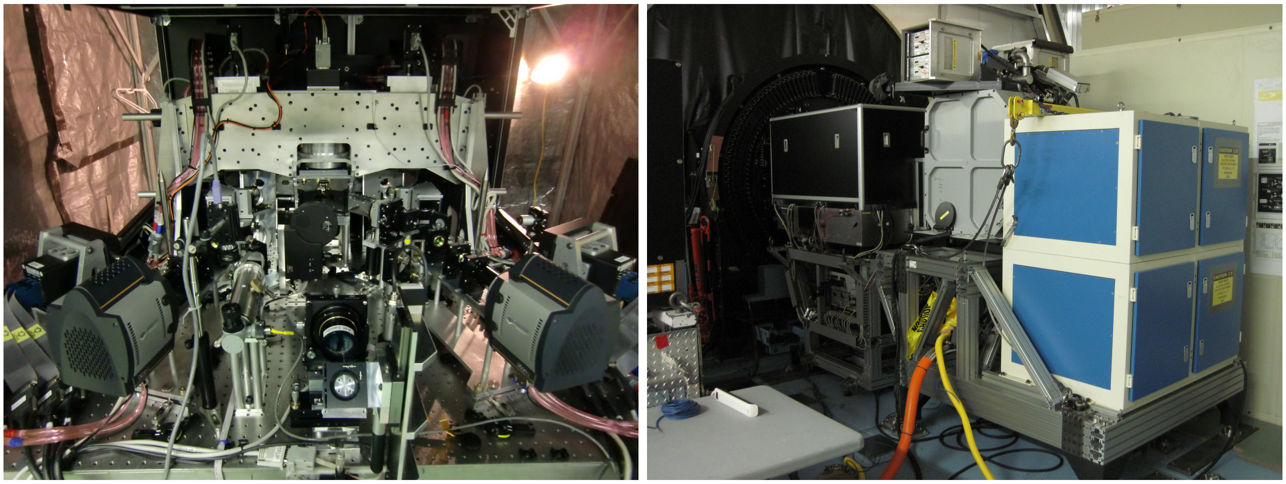
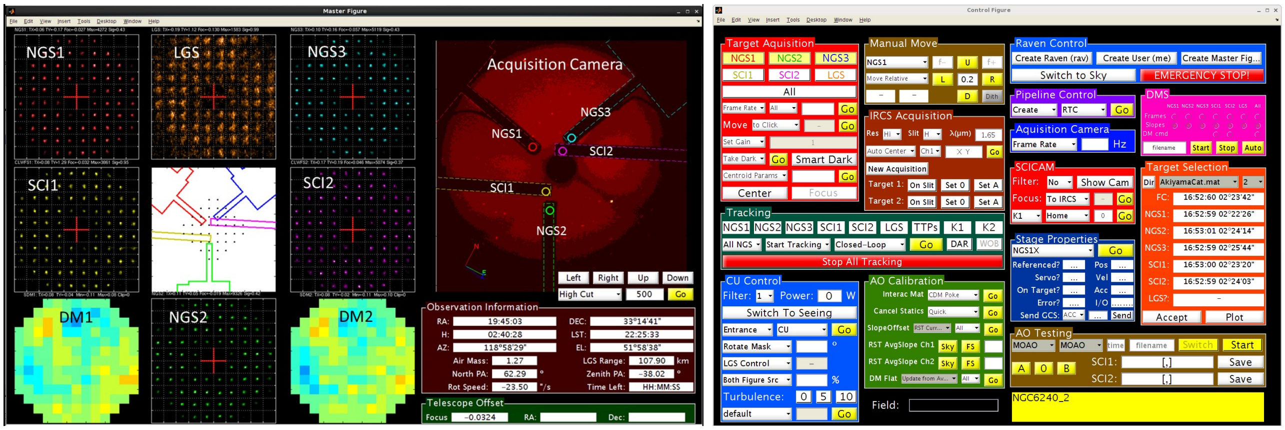


Figure 3. Raven opto-mechanical design.



(a) (b)

Figure 4. (a) Raven instrument.(b) Raven installed at the Nasmyth focus of Subaru Telescope next to the IRCS spectrograph (the grey box).



RA: 19:45:03
DEC: 33°14'41"
H: 02:40:28
LST: 22:25:33
AZ: 118°58'29"
EL: 51°58'38"
Air Mass: 1.27
LGS Range: 107.90 km
North PA: 62.29 °
Zenith PA: -38.02 °
Rot Speed: -23.50 °/s
Time Left: HH:MM:SS
Focus: -0.0324

Dir: AkiyamaCat.mat
FC: 16:52:60 02°23'42"
NGS1: 16:52:59 02°22'26"
NGS2: 16:53:01 02°24'14"
NGS3: 16:52:59 02°25'44"
SCI1: 16:53:00 02°23'20"
SCI2: 16:52:59 02°24'03"

(a) (b)

Figure 5. Raven GUI. (a) Panel showing a live display of the acquisition camera, WFS spots and DM commands during observation. (b) Panel controlling all the subsystems of Raven.

4. AO ENGINEERING RESULTS

Raven is an AO system able to operate in classic single–conjugated closed-loop AO (SCAO) mode 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. The inputs of the model are the relative positions of the NGSs and science targets, the Fried parameter, the C_n^2 profile, and optionally the wind profile. These atmospheric parameters are directly derived from the OL-WFS data acquired on-the-fly during AO corrections, using a SLODAR technique.[5,6]

The wind profile is only required for predictive[7,8] or multi-time step[9] tomographic reconstructors. In theory, these two advanced algorithms improve the AO correction by mitigating the lag error or by extending the corrected FoV respectively.

Figure 6 displays the images obtained for both science channels on an engineering field for different AO modes without the aid of the LGS.

The bottom-right panel plots the ensquared energy (EE) versus the seeing for all AO modes. As expected MOAO performance stands in between SCAO and GLAO. It is worth noting than most of the time, the turbulence was dominated by the ground-layer, making GLAO as good as MOAO (Fig. 7).

This level of performance are in fairly good agreement with the simulations including implementation errors[10] and meet the science requirements when the seeing is lower than 0.5 arcsec.

5. MOAO SCIENCE RESULTS

About 4 nights with Raven have been fully devoted to science. Targets were selected at low galactic latitudes to maximize chances of finding a suitable guide star asterism. The selected science cases must also make a good use of the multiplex or simultaneity advantage of Raven. Four science cases have been successfully observed with Raven and in each case a paper is either already published or in preparation:

- Metal-poor stars near the galactic center (PIs: Kim Venn and Masen Lamb),
- Stellar population of obscured star clusters and nearby galaxies (PI: Tim Davidge),
- Super Massive Black Hole in the southern core of NGC6240 (PI: Masayuki Akiyama),
- Resolving host galaxies of quasars (PI: Malte Schramm).

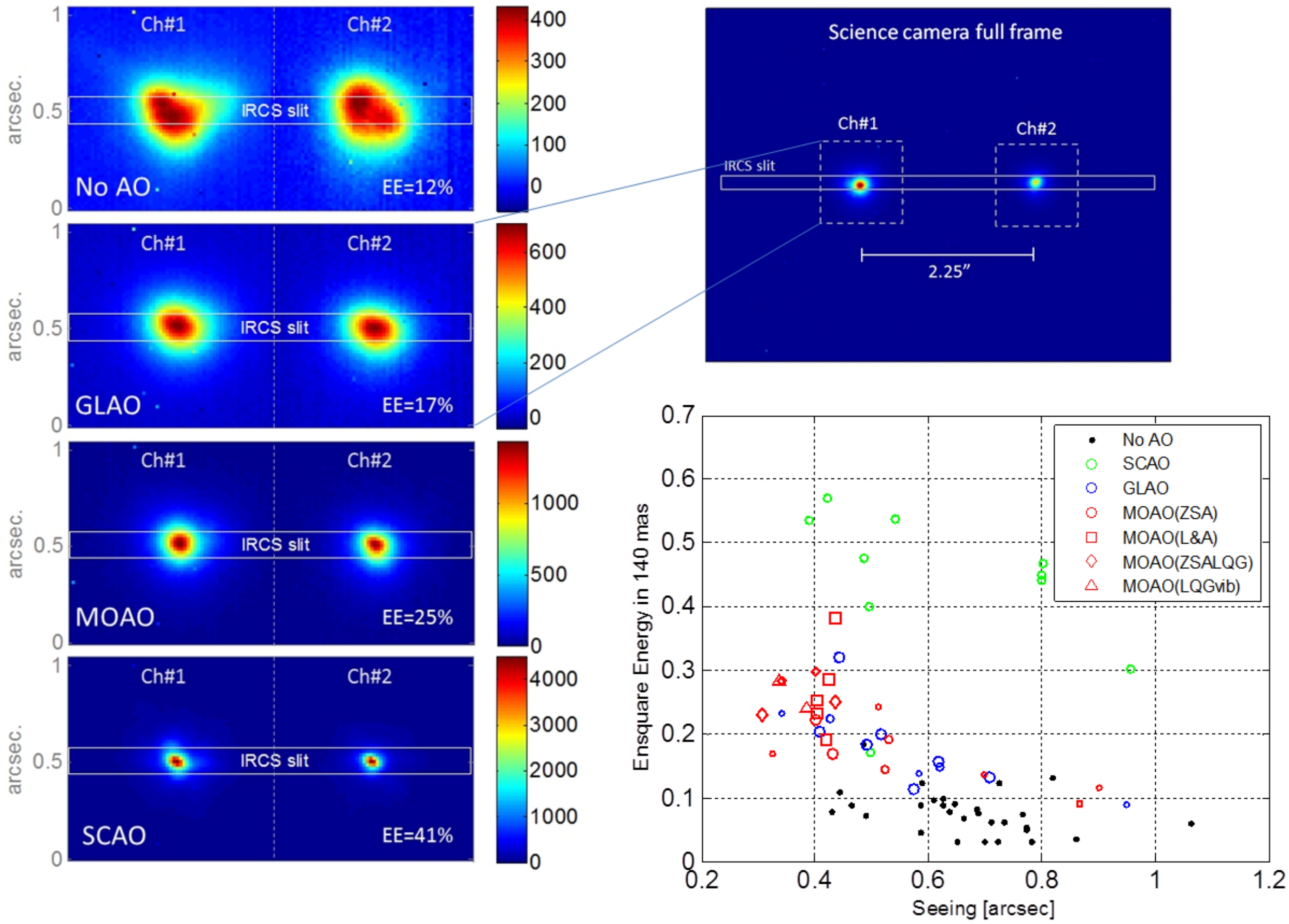


Figure 6. On-sky AO results obtained on engineering fields in May and August 2014. Top-right panel: Full frame of the Raven science camera showing the two science channels reimaged side-by-side ($\lambda = 1.0 - 1.7\mu m$). Left panel: Close-up of the science channel PSFs for different AO modes.The frame rate of all NGS WFS camera is 100Hz. 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. Bottom-right panel: EE obtained on IRCS imaging detector for different AO corrections as a function of the seeing. Different MOAO reconstructors have been tested: the Zonal Spatio-Angular (ZSA),[7] the raw Learn&Apply (L&A),[11] the Linear Quadratic Gaussian (ZSALQG)[12] and the same LQG with vibration cancellation (LQGvib).

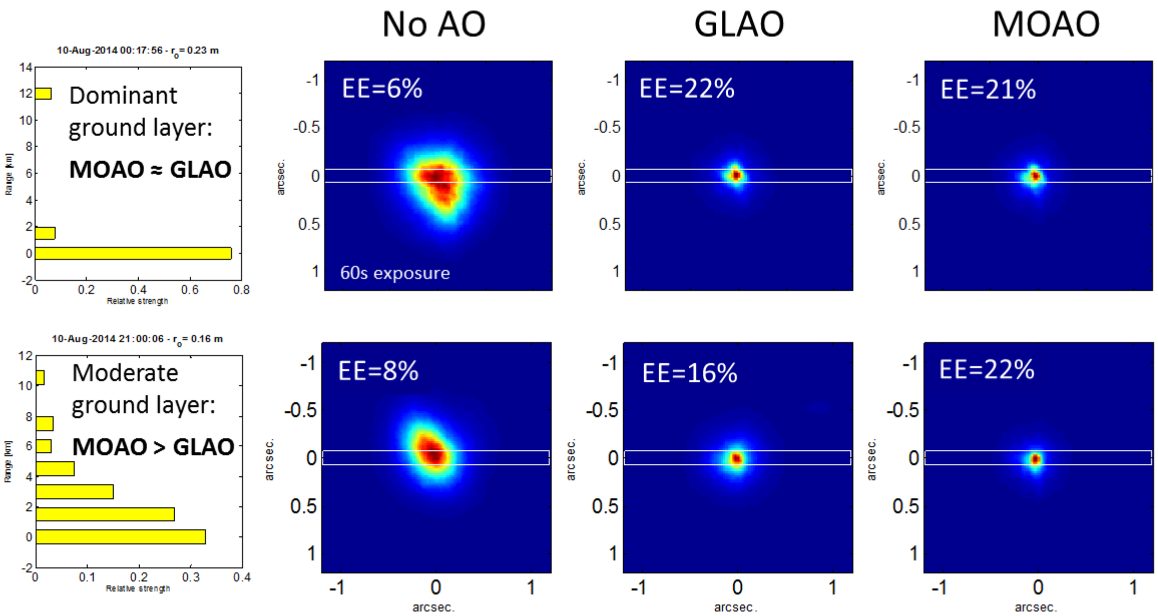


Figure 7. Impact of the turbulence profile on MOAO and GLAO performance. During our 3 runs, the turbulence was dominated by the ground-layer 75% of the time, making GLAO almost as good as MOAO.

5.1 Metal-poor stars near the galactic center

This science case used the spectroscopic echelle mode of IRCS and the two science targets are metal-poor stars with R magnitude of 11–15. 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 a 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.

For this science case, two types of targets have been observed:

- Globular cluster M22 stars (MA4 and MA4.1) to determine the spread in iron abundance. This cluster is a good target to observe since it is in a dense field (galactic center) and it is obscured by dust, so IR observations are ideal. We find no iron spread, which confirm recent independent observations.
- Metal-poor candidate stars in the galactic center (MA8, MA11, and MA14), to confirm their low metallicities. There are very few stars with low metallicities in the galactic center and observations need to use adaptive optics to resolve stars in those crowded regions. We find some of the lowest metallicity stars to date in the galactic centre with these Raven observations.

Figure 8 presents the echelle spectra obtained with IRCS spectrograph. More details about these science results can be found in Ref. 13.

5.2 Stellar population of obscured star clusters and nearby galaxies

Two obscured star clusters (GLIMPSE C01 and C02) and nearby galaxies (Maffei 1 and SagDIG) have been observed in H and K bands with Raven and IRCS grism mode (R$\sim$730 in H). The processing of GLIMPSE cluster data is still ongoing, but science results from Maffei 1 observation have already been published in Ref. 14.

Maffei 1 is one of the closest classical elliptical galaxies, with a distance comparable to that of Cen A. This galaxy has not been extensively studied, as it is located along the galactic plane, with A_V=4.7 mag. Maffei 1 has tantalizing hints of recent star-forming activity:

- H_β equivalent width is 3.6 Å, which is very high for nearby early type galaxies,

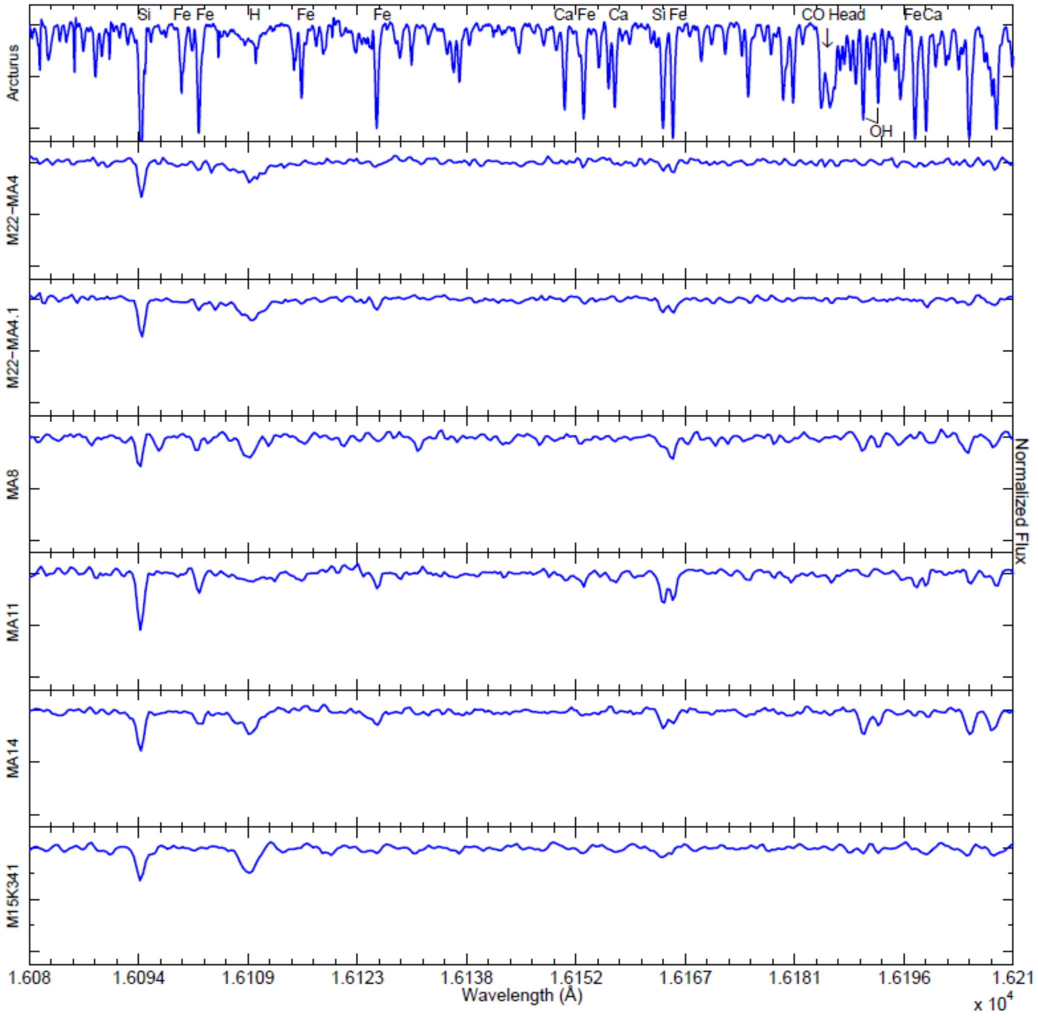
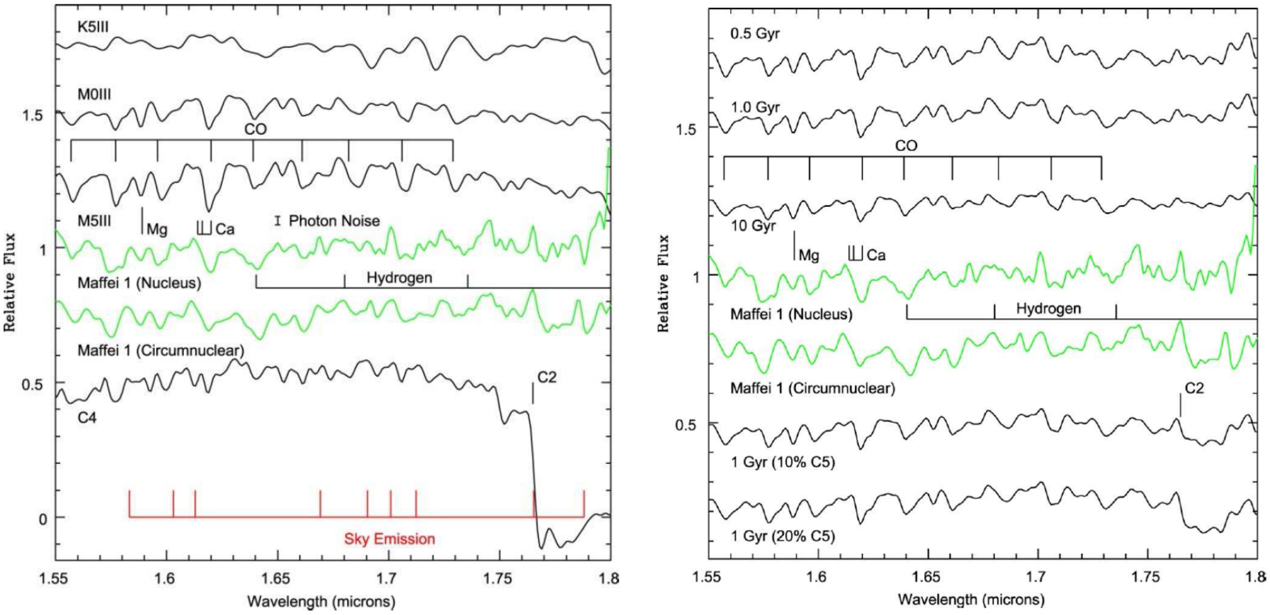


Figure 8. MOAO-corrected spectra of metal-poor stars observed near the galactic center with Raven and IRCS. The spectra of the main science targets (MA4, MA8, MA11, MA14) are compared to Arcturus, a standard metal-rich star, and to a metal-poor star in M15 globular cluster. H-band echelle mode, R= 20000, total exposure: from 30 to 180 minutes depending on the target brightness.



(a) (b)

Figure 9. (a) Spectra of the nucleus and circumnuclear regions of Maffei 1 observed with Raven and IRCS (green curves). The absorption spectrum is dominated by blends of molecular CO and atomic transitions. An absorption trough is detected longward of 1.76 μm that is not present in the spectra of O-rich K,M giants. The trough matches a feature in C star spectra that is due to C2. The feature is more pronounced in the circumnuclear spectrum. (b) The baseline models did not include C stars, and did not match the absorption trough longward of 1.76 μm. A 10-20% contribution from stars of type C5 can reproduce the depth of the C2 feature.

- there is a population of blue globular clusters candidates,
- there is a nucleus with a blue color at visible wavelengths and a red color in the near infrared.

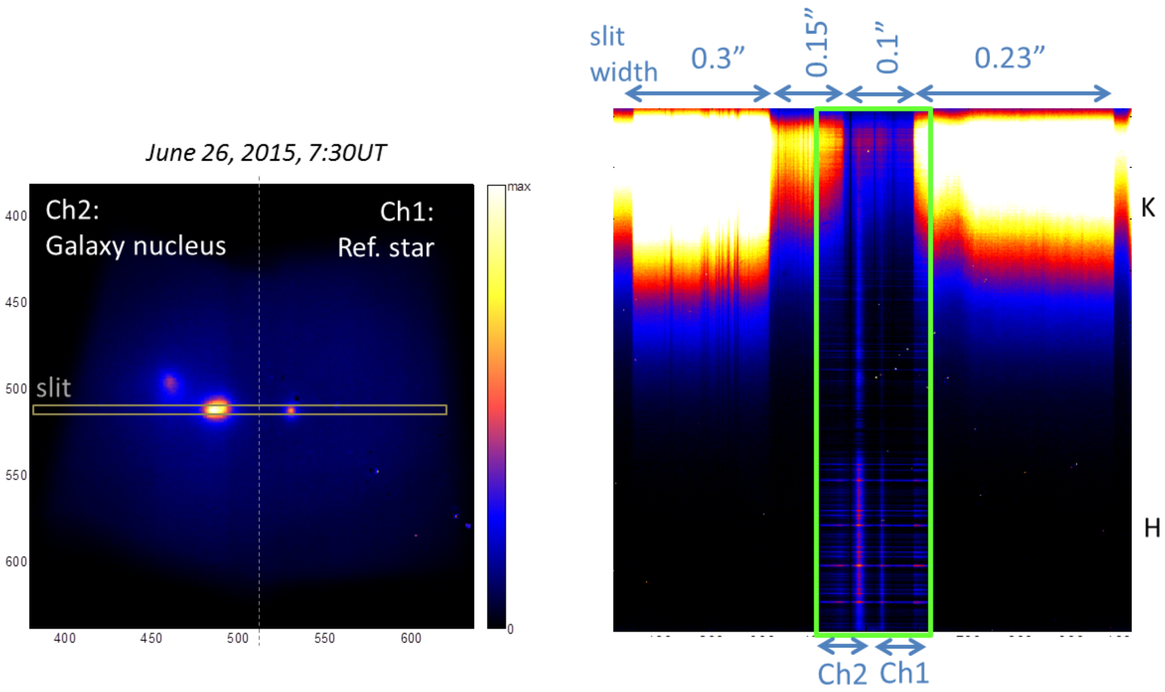
One science pickoff arm of Raven was on the nucleus region while the second arm was probing circumnuclear regions of Maffei 1. Comparison of Raven/IRCS spectra with abundance models suggests the presence of an intermediate age population with 10 to 20% of carbon stars (Fig. 9). The near-infrared colors of Maffei 1 are also indicative of a large population with an age similar to that expected to produce C stars. Maffei 1 is probably an E+A galaxy.

5.3 Super Massive Black Hole in the southern core of NGC6240

NGC6240 is a nearby ultra-luminous infrared merging galaxy with 2 distinct active nuclei obscured by dust. The goal of this observation is to determine the mass of the super massive black hole in the southern core of NGC6240.

The main challenge of this observation is the important atmospheric absorption of the Pa-α emission line used to derive the mass of the black hole. This emission line is unfortunately located in the middle of an atmospheric absorption band (between H and K bands). Thus, accurate correction for the atmospheric absorption is necessary to determine the velocity profile of the (broad) emission line.

The method is to use Raven and H-K grism spectroscopy with IRCS covering Pa-α broad emission line. The second pick-off arm of Raven is observing a reference star in order to monitor simultaneously the time variation of the atmospheric absorption. Raw IRCS images and spectra are displayed in Fig. 10, but data processing is still ongoing.



(a) (b)

Figure 10. Observation of the southern core of NGC6240. (a) Slit viewer showing the 2 science channel images: one channel is on the nucleus and the other on a reference star monitoring the atmospheric absorption. (b) Raw spectra of the nucleus and the reference star.

5.4 Resolving host galaxies of quasars

Malte Schramm (Univ. of Tokyo) got two nights under open-use time. The goal of his observation is to resolve the underlying host galaxy of z$\sim$3 quasars to study the black hole and galaxy co-evolution in the early universe. There is a strong synergy between Raven and ALMA. Both instruments provide images of similar resolution, and Raven probes the stellar component while ALMA probes the gas.

The main issue with this science case is the high contrast ratio between the bright AGN in the center and the very faint host galaxies. The idea to overcome this issue is to observe simultaneously the quasar and a nearby reference star with the two science probe arms of Raven. Then the PSF of the reference star is subtracted to the image of the quasar in order to remove most of the quasar’s contribution and emphasize the underlying host galaxy.

In order to work perfectly, this PSF subtraction technique requires the same PSF for the quasar and the reference star, 15 to 120 arcseconds away. Anisoplanetism is the main offender, but MOAO-corrected PSF are expected to be more uniform across the field than SCAO-corrected PSFs.

A total exposure of 3 hours has been collected on targets in H and K bands with 0.1”–0.35” residual seeing (0.2” average). A 4-point dithering has been used to mitigate the impact of bad pixels and the field rotation has been compensated with Raven K-mirrors. No science results are published yet, data processing is ongoing.

6. CONCLUSION

Raven is a MOAO science demonstrator which successfully got its first light on Subaru Telescope in May 2014, with two subsequent runs in August 2014 and June 2015. Raven is the first MOAO instrument installed on a 8 meter-class telescope capable of feeding two independent channels to a science instrument (IRCS spectrograph).

Raven was the first demonstration of MOAO-assisted spectroscopy. One MOAO science paper is already published, four to five more science papers are in preparation based on Raven observations. All the telemetry data collected by Raven's WFSs during the three runs are a gold mine for AO engineering, still to be explored, in order to learn more about the turbulence characteristics above Mauna Kea or to improve performance of advanced tomographic reconstructors contemplated for future MOAO systems on ELTs.

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