Design of the Calibration Unit for the MOAO Demonstrator RAVEN

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Abstract. The UVic AO Lab in collaboration with HIA and the Subaru telescope is currently designing Raven, a multi-object adaptive optics (MOAO) demonstrator that will be coupled to the Subaru Infrared Camera and Spectrograph (IRCS). Its main goal will be to demonstrate MOAO feasibility on the sky while allowing astronomers to beneficiate from the increased observing efficiency associated with such systems. INO is responsible for the Raven calibration unit design, fabrication and test. This sub-system consists in a telescope and turbulence simulator that will allow aligning Raven's components during its integration, testing its AO performances in the laboratory and at the telescope, and calibrating the AO system by building the interaction matrix and measuring the non-common path aberrations (NCPA). This sub-system is described in this paper. Its main challenges are to ensure that all the focal plane and pupil plane requirements will be met when considering manufacturing and alignment errors over its full waveband and across its field-of-view. This system is to be designed, fabricated and testes in seven months.

1. Introduction

Multi-object adaptive optics (MOAO) has generated considerable interest in the astronomical community over the last few years. Its capacity to reach higher Strehl ratios than other wide-field adaptive optics systems (AO) such as ground layer adaptive optics (GLAO) and multi-conjugate adaptive optics (MCAO) simultaneously on multiple objects makes it an instrument of choice for future extremely large telescopes. Its multiplexing capacity will allow gaining significantly in efficiency while addressing some of these telescopes key science cases. IRMOS [1, 2] for the TMT and EAGLE [3] for the E-ELT are two examples of such planned instruments.

The development of MOAO systems, however, represents some major technical challenges which led TMT and the E-ELT to postpone their development to the second or third generation of instruments. This also led to the design of several pathfinders such as ViLLaGEs [4], VOLT [5], Canary [6] and Raven [7, 8] to overcome these challenges and mitigate the associated risks.

Raven is the MOAO demonstrator being developed by the UVic AO Lab in collaboration with the HIA and the Subaru Telescope. It distinguishes itself from the other pathfinders by allowing the astronomical community to get scientifically meaningful data from an 8-m class telescope. It will have the ability to use three natural guide stars (NGS) and one laser guide star (LGS). Two science targets can simultaneously be observed and will be fed to the Subaru infrared camera and spectrograph (IRCS).

INO is designing, fabricating and testing the calibration unit for Raven. It consists in a Subaru Telescope and turbulence simulator. It will provide a square pattern of NGS sources over a FoV greater than 2' and a 0.6 to 1.8 µm (goal of 2.5 µm) waveband, a laser guide star at 590 nm conjugated to altitudes ranging from 85 to 180 km, and a bright alignment source to define the optical axis during Raven integration. The goal is to deliver a functional system in seven months.

2. System overview

The system is divided in 6 opto-mechanical sub-systems: the NGS illumination, the pinhole mask, the LGS and alignment sources, the optical relay, the phase screens and the system mechanical structure. These sub-systems are shown in Figure 1.

The main goal of the NGS illumination sub-system is to uniformly illuminate a pinhole mask on a field greater than 2' (64 mm in Raven focal plane) in the 0.6 µm to 1.8 µm (goal of 2.5 µm) spectral band in order to simulate NGS sources. Stars with magnitudes ranging from R < 10 to R=16 are emulated by selecting different ND filters placed in a filter wheel. The pupil is uniformly illuminated for all field positions.

The second sub-system is the pinhole mask. It consists in two sets of pinholes: seeing-limited (340 µm diameter) and diffraction limited above 1.0 µm (10 µm diameter). The holes are placed on a square pattern and are required to rotate at a speed up to 10 arcmin/second to simulate sky rotation. A second mask is used to select either the seeing limited or diffraction limited pinhole pattern.

The third sub-system is composed of the LGS and alignment sources. The LGS source is a CY5111A-WY LED from Roithner LaserTechnik emitting at 590 nm. The LED lens is flat polished to uniformly illuminate the pupil. A 400 µm pinhole is placed in front of the LED to set an average LGS full-width-half-maximum (FWHM) of 1.2" on the sky. The components are mounted on a translation stage to allow an altitude conjugation ranging from 85 to 180 km.

The alignment source is conjugated to infinity and its goal is to ensure that one beam path is visible by eye during the Raven integration phase. To do so, a Golden Dragon LED (LUW W5SM) from Osram is aligned on the optical axis. It is combined to the LGS by a 50/50 beamsplitter. A window is used to compensate for aberrations introduced by the beamsplitter combing the LGS and alignment sources to the NGS sources.

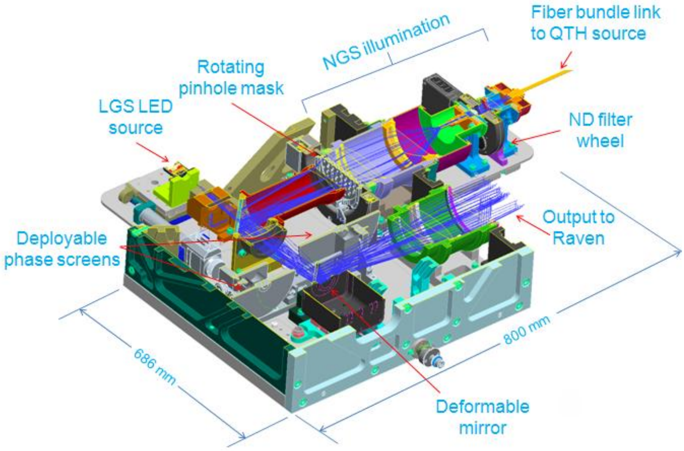

Fig. 1. Raven calibration unit opto-mechanical assembly main components

The optical relay assembly reimages the NGS, the LGS and the alignment sources in the Raven focal plane as if they were coming from the Subaru telescope. It first consists in a collimating group composed of three lenses and a beamsplitter – R_{avg}(600-900 nm) > 90%, T(590 nm) > 5% - that combines the NGS sources with the LGS and alignment sources, a deformable mirror conjugated to the ground, an imaging group composed of three lenses and a deployable mirror that selects the beam coming from the CU when in place, and let pass the beam coming from the Subaru telescope over a FoV of 3.5' when placed in its off position. It also has a 50/50 beamsplitter in front of the DM to minimize the projection angle on the DM.

The phase screen sub-system is designed by the UVic AO lab and consists in two deployable phase screens conjugated to altitudes of 5 and 10 km. Their rotating speed can be adjusted to mimic different wind speeds.

The mechanical structure is designed to minimize the system flexion when it will be placed in the vertical position in front of Raven. It also closes the calibration unit to isolate it optically from Raven and avoid straylight contamination from one system to the other.

3. NGS illumination system

The selected approach for this sub-system is to use a halogen source for the simplicity of the approach and its flexibility when it comes to changing the pinhole mask. This type of source is also widely available, generates a continuous smooth spectrum over the spectral range of interest and is available in a wide range of powers. In order to minimize the source power that heats the Raven enclosure, the source housing is linked to the calibration unit by a fiber bundle cable. A light pipe homogenizing rod is to be used to smooth the optical fiber images and ensure a uniform pupil illumination. To avoid the premature aging of the lamp bulb when driven in a low power mode, the light intensity is modulated using neutral density (ND) filters. It is planned to use a filter wheel with 6 mounted ND filters.

The optical design configuration of the illumination optics consists of a COTS light source module from Newport, a custom-made fiber bundle (FB) made by CeramOptec, a lens coupling module from the FB to a COTS Light Pipe (LP), and a mask illumination optics from the LP to the projection relay optics, as shown in Figure 2.

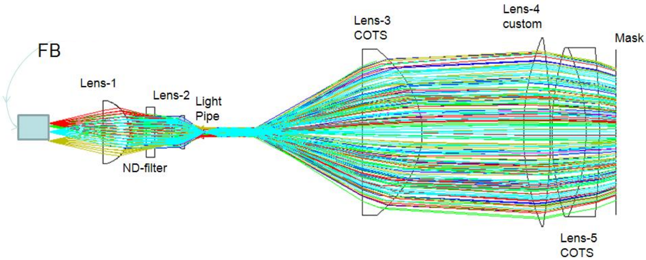

Fig. 2. Illumination optical system

4. Optical relay

4.1. Optical system

The optical relay goal is to reimage the NGS pinholes, the LGS source and the alignment source in the Raven focal plane as if they were coming from the Subaru Telescope. The main requirements optical requirements are summarized in Annex A. The exit pupil requirement is that it shall be at infinity and the combination of pupil shift and pupil magnification in function of FoV and wavelength should result in a ray position variation below 1% of the pupil diameter at the edge of the pupil. The calibration unit volume shall also not interfere with Raven and the Subaru structure, and a FoV of 3.5’ coming from the Subaru Telescope shall be cleared during Raven observations on the sky. This results in a back distance clearance between the last lens and the Raven focal plane of at least 325 mm. The system is to be operated in the -10° to 25°C temperature range.

The resulting optical system is composed of two groups: a collimating group projecting the pinholes at infinity and an imaging group generating the star images in the Raven focal plane. The back distance clearance and the field curvature requirement necessitate the use of a field lens close to the pinhole mask and prevent the use of identical symmetrical groups. The DM defines the optical system aperture stop. A first beamsplitter with a reflectivity > 90% in R-band and with transmission > 5% bellow 0.6 µm is used in the collimating group to combine the LGS and alignment sources to the

NGS sources. A second beamsplitter (50/50) is used in front of the DM to be at normal incidence and minimize projection angles effects. A deployable mirror can be controlled remotely to select the beam from the CU or let pass the beam from the telescope. The optical system is shown in Figure 3.

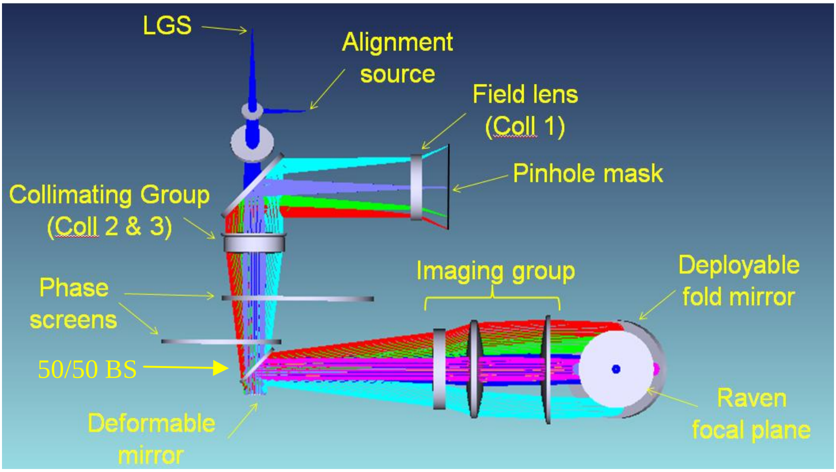

Fig. 3. LGS source, alignment source and optical relay optical systems

4.2. Ghost analysis

A ghost analysis was conducted in order to reduce the impact of ghost images on the system performances. It was assumed during this analysis that the lenses and beamsplitters non-splitting surfaces have an AR coating with an average 2% reflectivity and that the phase screens are uncoated (reflection of 4% per surface).

It is found that the parallel surfaces in the collimated beam of the beamsplitter and of the phase screens generate close to in-focus ghost images. The ghost image positions were controlled by tilting the phase screens and introducing a wedge between the beamsplitter faces. In more details, the following modifications are introduced:

- The 5 km phase screen is tilted by 0.25° along the same axis as the beamsplitter 45° tilt but in the opposite direction
- The 11 km phase screen is tilted by 0.5° in the same direction as the 5 km phase screen
- A 0.2° wedge is added between the 50/50 beamsplitter faces along the axis perpendicular to its 45° tilt

This brought the ghost images out of the Raven pick-up arm FoV.

4.3. Thermal analysis

The thermal analysis is conducted considering that the optical elements are mounted on aluminum (TCE= 23.5×10^{-6}). The simulated temperature ranged between -10 °C and 25 °C. All the requirements are still met over that thermal range with a focus compensation of 1.77 mm. As the distance between the calibration unit and Raven will be fixed, this compensation can be made by the calibration unit DM with a surface deformation of 0.45 µm peak-to valley. The different parameters variation with temperature is listed in Annex A.

4.4. Tolerance analysis

The strategy used to confirm that the optical requirements enumerated in section 4.1 will be met when considering manufacturing and alignment tolerances is addressed in this section since the Zemax tolerance tool alone do not allow to achieve this goal. First, 100 Monte Carlo files are generated and saved through a typical tolerance analysis in Zemax. Second, a macro is used to save all the relevant parameters to text files. These text files are loaded in Matlab and the expected performances with a 50% and 90% degree of confidence are extracted for each parameter. Results are reported in Annex A.

The mechanical approach to meet those tolerances is based on a method developed in house that minimizes the cost and the necessary adjustments to achieve the required tolerances. This method replaces the linear and RSS sums by a Monte Carlo statistical approach based on real statistical data. This allowed limiting the adjustment to two components in this system. The first adjustment is on the lightpipe centering and axial position to ensure that the DM is fully illuminated at all FoV and over the full waveband. The second adjustment is on the DM itself as the tolerances on the DM mechanical assembly provided by the manufacturer are not precise enough to meet its positioning tolerances. Moreover, the assembly is to be done at INO with a dummy DM mirror that will be replaced at the UVic AO lab by the real DM. Hence, a robust way of accurately positioning the DM is required. This is defined in the next section.

4.5. DM alignment plan

The strategy is to position a reference mirror conjugated to the DM nominal position in the 50/50 beamsplitter unused port with a precision of 10 µm in centering, 0.1° in tilt and 10 µm on its axial position. The goal is to achieve a DM positioning precision of 50 µm in centering, 0.1° in tilt and 50 µm on the axial position.

The DM is first roughly placed in its nominal position with mechanical references. The DM tilt is then finely adjusted by overlapping the 10 µm NGS pinhole images generated by the two mirrors. A tilt difference of 0.01° between the two mirrors leads to an image position difference of 100 µm in the focal plane which will be significantly above the minimal detectable image shift.

The two pupils associated with the on-axis seeing limited pinhole are then imaged on a sensor. The DM centering is adjusted so that the centroid of its pupil is aligned with the centroid of the reference mirror image. A precision of 50 µm is planned to be achieved.

The third step is to image the two pupils of a seeing limited pinholes close to the edge of the FoV on the sensor. The DM axial position is adjusted so that the centroid of the two pupils overlap.

5. Conclusions

The detailed tolerance analysis and the thermal analysis confirm that the requirements will be met over the thermal range with at least a 90% confidence level. The ghost images will not interfere with the main star images and an alignment strategy allowing UVic to replace the dummy DM with the real one with a minimum of equipment was proposed and tested using Zemax. The system delivery is still in line with the seven months goal at the end of the design phase.

6. References

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Annex A

Table 1 : Comparison between the optical parameters required values with the expected values

Parameter	Required value	Nominal Value @ -10 °C	Nominal Value @ 25 °C	With tolerances @ 20°C
Focal plane diameter	> 64 mm	86 mm	86 mm	No significant change with tolerances
Focal plane curvature	< 2.3 m	< 2.3 m	< 2.3 m	No significant change with tolerances
Coma	< 1.3 µm	< 0.01 µm	< 0.01 µm	No significant change with tolerances
Working F/#	13.6 +/- 0.3%	13.59	13.62	probability > 90% of being within the 13.60 +/- 0.04 (0.3%)
Exit pupil edge variation	~1%	1.1%	1.1%	90% confidence: 1.2% 50% confidence: 1.1%
FoV Relative illumination	> 50%	96%	96%	No significant change with tolerances
Image quality < 1µm	RMS spot size < 100 µm	< 40 µm	< 40 µm	No significant change with tolerances
Image quality > 1 µm	Diffraction limited (Strehl > 0.8)	Strehl > 0.89	Strehl > 0.86	90% confidence: Strehl > 0.8 for FoV < 35 mm
Lateral color between 0.6 < λ < 0.9 µm	≤ 100 µm @ 32 mm	~19 µm @ 32 mm ~65 µm @ 43 mm	~18 µm @ 32 mm ~65 µm @ 43 mm	No significant change with tolerances
Lateral color between 0.9 < λ < 1.8 µm	≤ 20 µm @ 32 mm	~10 µm @ 32 mm ~24 µm @ 43 mm	~10 µm @ 32 mm ~23 µm @ 43 mm	No significant change with tolerances
Axial color	< 580 µm	λ < 1.8 µm: 192 µm	λ < 1.8 µm: 173 µm	90% confidence: 220 µm 50% confidence: 160 µm
		λ < 2.5 µm: 595 µm	λ < 2.5 µm: 605 µm	90% confidence: 637 µm 50% confidence: 550 µm