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MOONS – multi-object spectroscopy for the VLT: DMD based instrument calibration

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ABSTRACT

The MOONS (Multiple-Object Optical and Near-infrared Spectrograph) is a fibre-fed spectrograph for the European Southern Observatory's Very Large Telescope. It will provide simultaneous observations of up to 1,000 objects covering the wavelength range 650 nm to 1800 nm. MOONS will also provide an observing mode with 500 object-sky pairs to provide precise sky-subtraction by nodding between object and sky. For this observing mode to be successful the instrument must be well calibrated and the relative throughput of each optical fibre known. The MOONS instrument throughput and wavelength calibration will be characterised, on a daily basis, using the on-board calibration system. The calibration system will illuminate the instrument via a deployable diffuse reflective screen located in front of the focal surface containing the optical fibres. The calibration system provides both spectral calibration via arc lamp illumination, and flat-field illumination via a Digital Micro-mirror Device (DMD) based projector system. This paper will provide a summary of the design and performance of the MOONS calibration system. Flat-field performance results will be presented which demonstrate the calibration unit achieves better than 2% peak to valley illumination uniformity across the 880 mm diameter flat-field screen.

Keywords: Calibration, Spectrograph, Digital Micro-mirror Device, Ground-based instruments, multi-object infrared spectrographs.

1. INTRODUCTION

The Multiple-Object Optical and Near-infrared Spectrograph (MOONS) is a new instrument being constructed for installation at the Nasmyth focus of the European Southern Observatory's Very Large Telescope (VLT). MOONS is designed to be a powerful spectroscopic survey instrument and has several key design features to maximize survey efficiency: it will observe the full 25 arc-minute field of view of the VLT, it will simultaneously observe up to 1,000 objects, and it will capture spectra over the broad wavelength range 650 nm to 1,800 nm.

The instrument consists of three sub-systems: the rotating front end, the spectrograph, and the control software. A full description is provided in [1] and [2]. The rotating front end is so called because it will be mounted to the Nasmyth rotator on the VLT. It contains a large field corrector lens, the focal plate with 1,000 fibre positioning units, field acquisition cameras, a metrology system, electronics, cable wrap and the calibration system [3]. There is a fibre link between the rotating front end and the spectrograph [4][5]. The spectrograph consists of two three-channel spectrographs mounted either side of an optical bench. Each three-channel spectrograph contains a slit, collimator, dichroic beam splitters, dispersing optics, mechanisms, and three cameras covering RI, YJ and H-bands [6]. The RI-band cameras are fitted with 4096 by 4096 pixel CCDs, and the YJ and H-band cameras are fitted with Teledyne H4RG detectors [7]. The entire spectrograph is housed within a large cryogenic vacuum chamber that cools the optical bench to an operational temperature of 130 K and the H4RG detectors to 40 K. MOONS has a sophisticated electronics control system [8] and the control software includes complex algorithms to perform simultaneous movements of all 1,000 fibre positioners [9].

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This paper will describe the *calibration system* in detail. The MOONS calibration system has two top level requirements:

1. To illuminate the instrument focal plane with light for wavelength calibration.
2. To *uniformly illuminate* the instrument focal plane with light to allow measurements of fibre transmission.

To achieve wavelength calibration, it was decided to illuminate the instrument with light from an arc lamp with a well characterized spectrum [2]. Thorium Argon hollow cathode arc lamps were selected for this purpose and will provide approximately 350 arc lines of observable intensity, over the MOONS wavelength range, as determined from the European Southern Obervatory's Thorium Argon arc line list.

The requirement to measure the fibre transmission comes from the need to provide accurate sky subtraction [1][10]. For example, if fibre A is used to observe object+sky, and fibre B is used to observe sky, then the relative transmission of fibres A and B must be known for the sky continuum to be correctly subtracted from the object+sky spectrum. The fibre transmission will be regularly measured during MOONS operations: high signal to noise measurements during daytime calibrations, and whilst observing, to detect any transmission changes caused by the movements of the fibre positioning units.

Providing a light source that uniformly illuminates a large field of view, within the tight space constraints of the rotating front end structure, has been a significant technical challenge. The solution was to develop a near-infrared digital projector system, under computer control, with imaging feedback [11]. The next section describes the design of the calibration system, and section 3 describes the integration and testing.

2. DESIGN OVERVIEW

The MOONS calibration system consists of four sub-systems: calibration unit, deployable screen, control electronics, and control software. The calibration unit, screen, and electronics cabinet will be mounted within the rotating frond end of the MOONS instrument [3].

A schematic of the layout of the calibration unit with respect to the screen, and the instrument's entrance focal surface, is shown in Figure 1. Light is projected from the calibration unit towards the screen, where it is diffusely reflected towards the fibres. The entrance focal surface of MOONS is located at the front of the fibre positioning units approximately 500 mm from the screen [3].

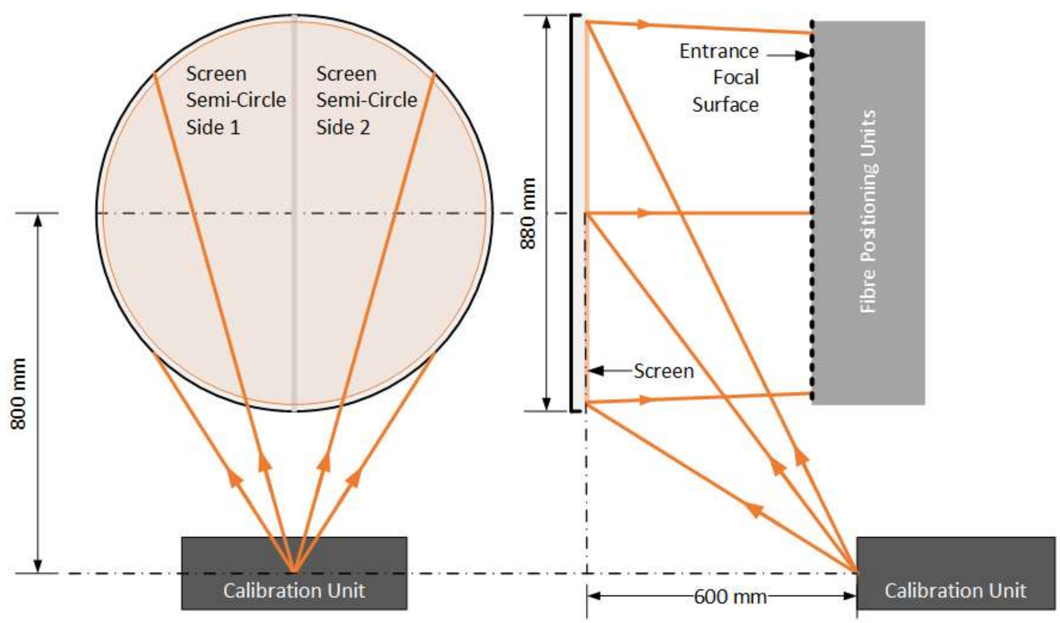

Figure 1. Schematic of the optical path from the calibration unit to the screen and from the screen to the fibre positioning units containing the optical fibres.

A picture of all calibration system hardware is shown in Figure 2. Both the calibration unit and the screen are mounted on an optical bench, for alignment and test purposes. The control electronics cabinet (named sub-cabinet #1) is located adjacent to the optical bench, mounted on a set of shelves.

The screen is 880 mm diameter and features two semi-circles mounted onto a support frame. Each semi-circular panel consists of an aluminium back plate coated with a highly reflective diffuse Lambertian coating. It is important that a Lambertian coating is used as it provides uniform reflectance versus angle. In operation the two halves of the screen will be mounted within the rotating front end structure on a mechanism. During science observations the screen will be open, to allow light to pass between the telescope and MOONS. During calibration observations the screen mechanism is closed to form a circular screen. As well as reflecting calibration light towards the optical fibres, the closed screen also acts as a shutter, and can prevent light from the telescope entering the instrument. The back of the semi-circular panel is painted with absorbing black paint [3]. For the flat-field to be uniform it is necessary to minimize the gap between the two panels when the screen is closed. This is straightforward to achieve in the laboratory, the joint is barely visible in Figure 2.

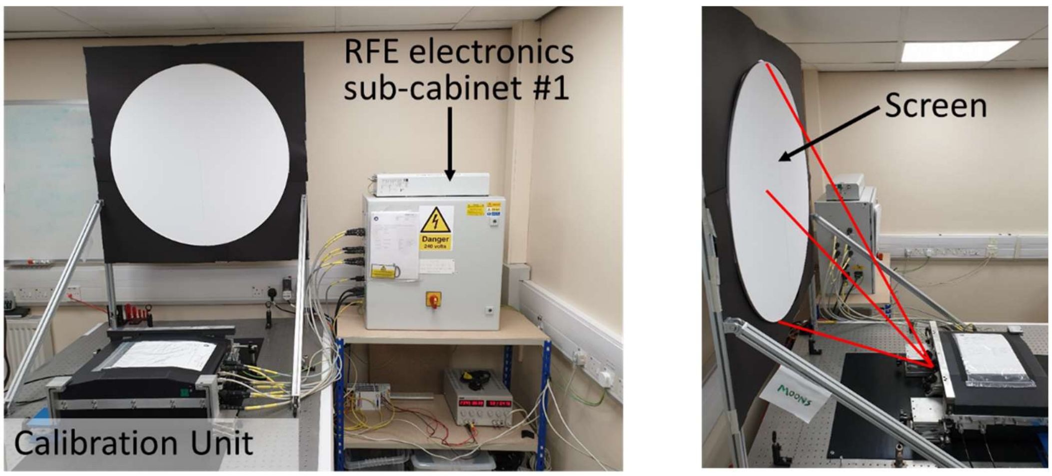

Figure 2. Picture of the MOONS calibration unit. The left-hand picture shows the calibration unit, the white diffuse screen, and the rotating front end electronics sub-cabinet #1. The red lines on the right-hand picture illustrate the light path from the projector to the screen.

The calibration unit is a light tight box and contains the opto-mechanical and electronics hardware to provide calibration illumination. It measures 160 mm by 400 mm by 500 mm and weighs 19 kg. Referring to the left-hand picture in Figure 2, the right-hand side of the calibration unit box contains a breakout panel for the electrical connectors. There is also an on-off switch. On the left-hand side of the calibration unit are inlet and outlet pipes for cooling fluid (mix of water and ethylene-glycol). The top of the unit has an access flap which can be opened to allow faulty light bulbs to be replaced. The optical path between the calibration unit and the screen is shown on the right of Figure 2. Note large angles of incidence at the screen, which made the design of the projector optics challenging [11]. Calibration light exits the unit via projection optics that can be seen in Figure 3.

The calibration unit contains two Photron P858A Thorium Argon hollow cathode arc lamps (astronomical calibration lamps). The output of these lamps is directed towards the screen via a prism and diverging optics, to ensure the entire screen is illuminated [11]. Each lamp is equipped with a photodiode feedback sensor so the control software can determine if the lamp is functioning correctly. The optical system for each hollow cathode arc lamp is equipped with a shutter, which is kept closed whilst the lamp warms up or cools down.

In the centre of Figure 3 is a convex gold mirror illuminated with red light. This is the output mirror of the infrared projector system that provides uniform flat-field illumination onto the screen. The optical design is based on a short throw projector, where distance between the projector and the screen is small, being only 600 mm for MOONS, as indicated in Figure 1. The optical design is described in [11]. In summary, the infrared projector consists of a quartz tungsten halogen lamp light source, a shutter, a motorized filter wheel, an optical system to couple light from the source to the DMD, the DMD and beam steering prisms, and projection optics to reimage the DMD image onto the screen. A picture of the DMD, displaying the MOONS logo, is shown in Figure 4. The light output appears orange/red as the projector optics are optimized for use at wavelengths greater than 650 nm (visible as red light). Immediately adjacent to the projector optics is a lens and CCD camera referred to as the *truth camera*. This camera provides feedback on the calibration unit's performance. It is used to capture an image of the illumination pattern on the flat-field screen which is used for diagnostic purposes, as described in the next section. The DMD is controlled by a small BeagleBone® Black computer located within the calibration unit. Images are sent to the DMD control computer, from the MOONS control computer, via ethernet cable.

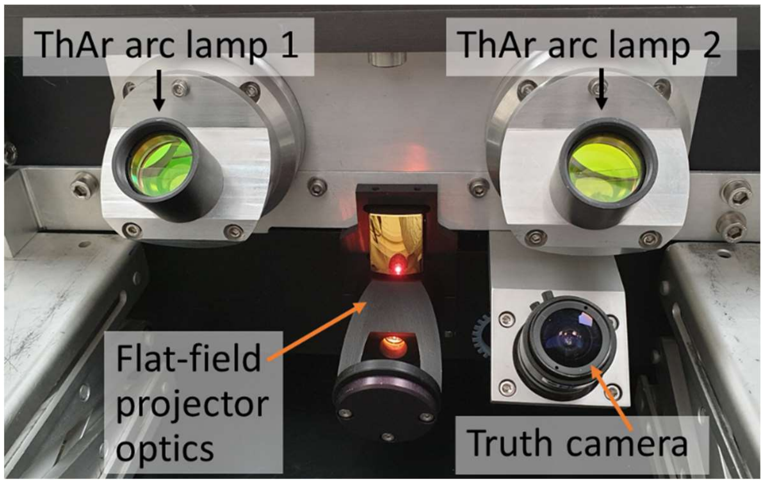

Figure 3. Picture of the various output optics on the calibration unit and the truth camera for imaging the screen.

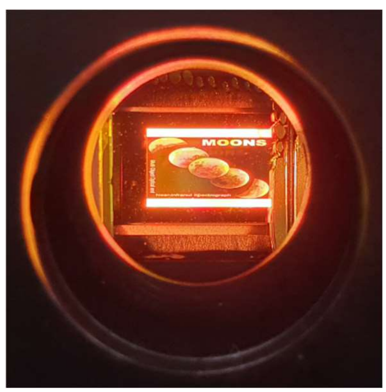

Figure 4. Picture of the digital micro-mirror device, taken during assembly of the infrared projector, displaying the MOONS logo. The active area of the DMD is 9.86 mm by 6.16 mm.

A quartz tungsten halogen lamp was chosen for the flat-field light source as the filament, which operates at approximately 3000 K, produces a smooth blackbody like spectrum. The lamp housing is mounted onto a cooling plate which stabilizes the lamp operating temperature and prevents overheating of the lamp. The temperature of the calibration unit is monitored during operation by four temperature sensors, providing feedback to the control software.

There are power supplies within the calibration unit for the quartz tungsten halogen lamp, photodiode sensors, and shutters. The two large power supplies for the arc lamps are located within the electronics cabinet. This cabinet also contains power conditioning equipment, and various Beckhoff modules such as: solid state relays, temperature feedback, and control for the filter wheel motor. The cabinet is a standard size, 600 mm by 600 mm by 350 mm, and weighs 65 kg.

All the calibration unit functions are under software control from the MOONS rotating front end workstation. The bespoke software for controlling the flat-field image, developed at the UK Astronomy Technology Centre, is described in the next section.

3. INTEGRATION AND TEST RESULTS

The assembly phase of the calibration unit was described previously [11]. Final integration and testing of the MOONS calibration system was carried out in an optical laboratory with the calibration unit, and screen mounted onto an optical bench, as shown in Figure 2. The alignment of the projector with respect to the screen was carefully adjusted to ensure the projected DMD image is correctly centred on the screen. All flat-field tests were performed in dark conditions as stray light will affect the measured uniformity.

The truth camera is equipped with a wide-angle lens which views the screen at an angle of incidence of approximately 45 degrees. This causes the truth camera image to be quite distorted, as can be seen in the centre image in Figure 5. To map the distortion in the truth camera image a standard chessboard target is used, located at the screen, as shown on the left of Figure 5. Several images of the chessboard target are taken with the chessboard moved between each image. This provides good sampling of the distortion parameters over the field of view of the truth camera. The MOONS calibration unit software automatically measures the locations of the distorted chessboard squares, for each image, and calculates distortion coefficients. From these coefficients an inverse transformation matrix is calculated, which is applied to the truth camera image, resulting in a corrected image, as shown on the right of Figure 5. The distortion transformation maintains the pixel intensity values at the correct level so that the level of illumination on the screen can be quantified. Note that the distortion transformation is only applicable to the area occupied by the screen. Outside this corrected area the image still has some residual distortion.

Figure 5. Left – picture of a chessboard distortion calibration target located on the calibration screen. Centre – truth camera image of the chessboard target, the image is distorted. Right – truth camera image following distortion correction.

The procedure for projecting a uniform flat-field onto the screen is summarized in the following steps:

1. Calibrate truth camera, measure distortion and flat-field correction, see Figure 5.
2. Project an initial DMD pattern, intensity level is RGB = 150 for all DMD pixels.
3. Capture a truth camera image and apply distortion correction, see Figure 6 and Figure 7.
4. Calculate intensity correction factors for next DMD image. Trim edges of DMD image.
5. Project new image, flat-field correction iteration count = 1.
6. Capture a truth camera image and apply distortion correction.
7. Check if new screen illumination pattern meets uniformity requirements. If further correction is required, then proceed to the next step.
8. Calculate intensity correction factors for next DMD image. Trim edges of DMD image.
9. Project new image, flat-field correction iteration count = count +1.
10. Repeat steps 6 – 9 until the projected image is uniform. A uniform image is shown in Figure 8.

The following figure shows an example of the calibration unit in operation, with the DMD projecting an initial image with all pixels set to RGB = 150. The image on the left of Figure 6 shows the raw truth camera image. The image on the right of Figure 6 has been distortion corrected. The illumination pattern on the screen can be seen to be slightly non-uniform. The calibration unit software uses this image to calculate how the intensity as a function of pixel position on the DMD needs to be changed to result in the projected output achieving uniform illumination.

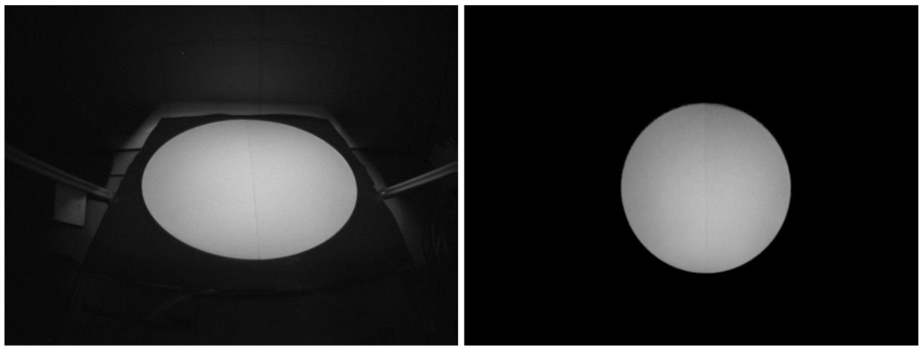

Figure 6. Left – truth camera image of the screen illuminated with all DMD pixels set to RGB = 150. Right – truth camera image after distortion correction. At this stage the illumination pattern is non-uniform.

The results of the software analysis of Figure 6 are shown in the plots in Figure 7. The measured intensity variation across the screen is approximately 40%.

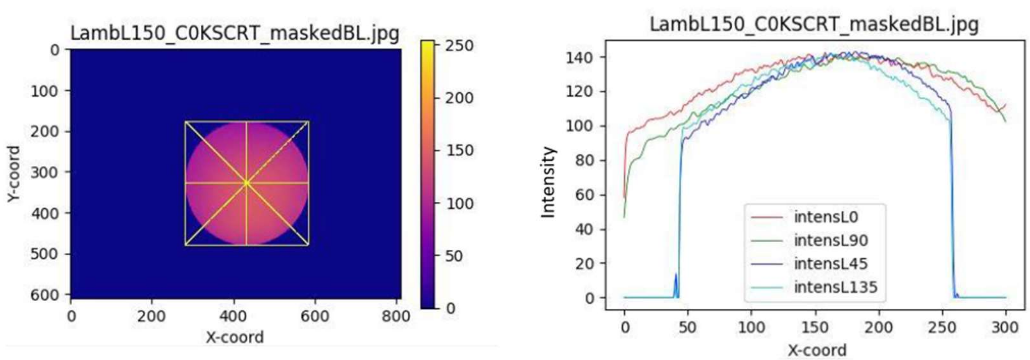

Figure 7. Truth camera results for an initial projected image with all pixels set to RGB = 150. The left-hand plot shows the image with yellow lines superimposed to indicate the analysis regions. The right-hand plot shows the intensity versus pixel positions as measured along the four yellow lines that pass through the centre of the image. Both plots show the intensity is higher at the centre of the screen implying correction is needed.

Following seven iterations by the calibration unit software the results for the final flat-field are shown in Figure 8. This image can be seen to be significantly more uniform. The MOONS optical fibres will view a smoother version of this image, as the field of view of a fibre projected onto the screen is 30 mm diameter. The intensity variation across the screen, as viewed by the fibres, is less than 1%.

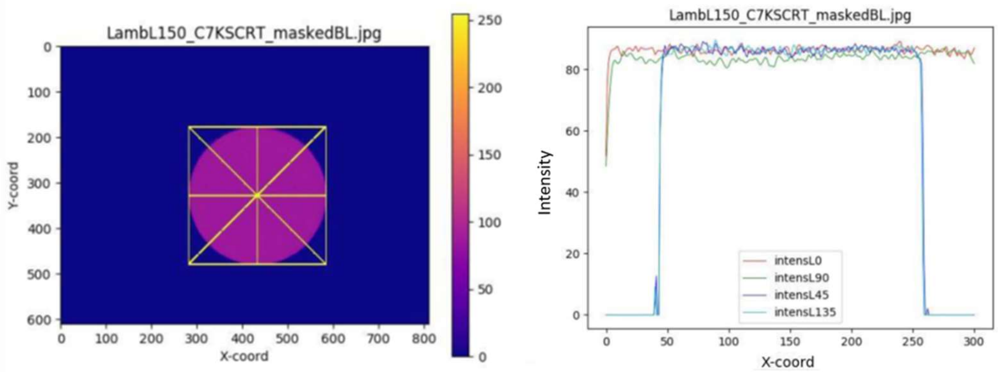

Figure 8. Truth camera results after seven iterations of the procedure to produce uniform illumination on the screen. The left-hand plot shows the image with yellow lines superimposed to indicate the analysis region. The right-hand plot shows the intensity versus pixel positions as measured along the four yellow lines that pass through the centre of the image. Both plots show the intensity is now uniform across the screen.

The results from the truth camera were independently verified with an on-axis CCD radiometer.

It is likely that the distortion and flat-field correction will need to be repeated when the calibration unit and screen are fitted to the rotating front end. Small changes in alignment will change the flat-field uniformity. This will be done at the UK Astronomy Technology Centre during final instrument acceptance testing. Once the instrument is in a stable location on the VLT's Nasmyth platform the flat-field should remain stable. A small adjustment might be needed following replacement of the quartz tungsten halogen lamp.

4. SUMMARY AND CONCLUSIONS

This paper provided an overview of the MOONS instrument and the top-level requirements for the calibration system. The three hardware sub-systems that make up the calibration unit: electronics, screen, and calibration unit light projection system, were described in detail. The integration and test procedure for the calibration unit was presented, including details of how the uniform flat-field illumination is achieved. After correction, the final projected flat-field image has intensity variations at the 1% level. This will enable precise measurement of the throughput of each optical fibre, to be done during daytime calibration observations, and during the night during target acquisition and setup. The design, development, and testing of the calibration unit is now complete, and it is ready to be installed on the rotating front end, after which final acceptance tests will be performed.

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