Rising MOONS: an update on the VLT’s next multi-object spectrograph as it begins to grow

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ABSTRACT

After completion of its final-design review last year, it is full steam ahead for the construction of the Multi Object Optical and Near-infrared Spectrograph (MOONS) instrument - the next generation multi-object spectrograph for the VLT. This remarkable instrument will combine for the first time: the 8 m collecting power of the VLT, 1001 optical fibers with individual robotic positioners and both medium- and high-resolution spectral coverage across the wavelength range 0.65μm - 1.8 μm. Such a facility will allow a veritable host of Galactic, Extragalactic and Cosmological questions to be addressed. In this paper we will report on the current status of the instrument, details of the early testing of key components and the major milestones towards its delivery to the telescope.

Keywords: Multi-object Spectrograph,

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1. INTRODUCTION

We are entering a new era in massive multiplexed Multi-Object Spectrometers (MOS). A number of instruments with the capability to study thousands of objects are currently under construction, e.g. PFS\(^1\), DESI\(^2\), WEAVE\(^3\), 4MOST\(^4\). Naturally these instruments are tailored to different science cases and different telescopes, so making direct comparisons can often be misleading, but we can try. Consider that MOONS will be mounted at the VLT, so immediately has more collecting area than other MOSs on 4m class telescopes and therefore greater sensitivity. It will use the full 25' diameter field of view of the VLT and will have 1001 fibers, which is a significant increase on many existing 8 m class facilities. But perhaps the most unique aspect of MOONS, and what really sets it apart, is that it will go further into the infrared, see Figure 1, thus opening up a range of nearly unique science cases.

Within this paper we will briefly assess the science that MOONS will enable, before presenting an overview of the instrument. We will then delve into further detail of various sections of the instrument, picking out particular design highlights and challenges that have arisen. Nearly all aspects of the design are finalized and many components are now being manufactured, so this paper hopefully represents a suitable snapshot of this remarkable instrument as its construction begins in earnest.

![Comparison of the wavelength coverage for many of the major MOS instruments that will soon be on sky.](image)

Figure 1. Comparison of the wavelength coverage for many of the major MOS instruments that will soon be on sky.

2. WHY ARE WE BUILDING IT?

Combined with the power of the VLT, the unique capabilities of MOONS will provide the tools necessary to study galaxy formation and evolution over most of the history of the Universe with unprecedented accuracy. MOONS will enable the study of the different mechanisms by which galaxies form and evolve throughout an impressive range of cosmic times, from investigating the properties of millions of stars in the centre of our own Milky Way to millions of galaxies in the early Universe.

2.1 Galactic science case

The study of resolved stellar populations of the Milky Way and other Local Group galaxies can provide us with a fossil record of their chemo-dynamical and star-formation histories over many gigayear timescales. The Milky Way is the only galaxy whose components can all be resolved into individual stars with current telescopes. As such it is an ideal, and indeed, unique laboratory to investigate the details of the processes behind formation and evolution of a disc galaxy. As a result, the need to obtain a large-scale empirical description of the Milky Way has defined the ambitious requirements of large photometric and spectroscopic surveys during the last decade.

The Gaia mission is now providing the community with high-precision positional measurements of about one billion stars, with dedicated ground-based surveys (Gaia-ESO\(^5\), GALAH\(^6\)) in place or planned to provide the spectroscopy for chemistry and kinematics. MOONS has been designed for accurate determination of stellar abundances such as alpha, light, iron-peak, neutron-capture elements. Therefore, MOONS will provide this crucial follow-up for Gaia and for other Galactic surveys with the VISTA telescope (as well as the southern regions observed by Pan-STARRS and UKIDSS), delivering accurate radial velocities, metallicities and chemical abundances for several million stars over its lifetime.
2.2 Extra-Galactic Science

Tracing the assembly history of galaxies over cosmic time remains a primary goal for observational and theoretical studies of the Universe. In recent years, large spectroscopic surveys at optical wavelengths (0.3 \(\mu\)m – 1 \(\mu\)m) have provided important information on the formation and evolution of galaxies, but near-IR spectroscopy is now required to extend our knowledge beyond \(z>1\). In fact, at these redshifts almost all the main spectral features used to determine the physical, chemical and dynamical properties of galaxies are shifted to \(\lambda > 1 \mu\)m (e.g. H\(\alpha\), OIII, Ca HK).

MOONS will provide high-quality spectra for a statistically significant number of galaxies (i.e. > 1 million) at \(z > 1\) for the first time, matching a similar rest-frame wavelength, volume, range of environments and stellar masses as the successful Sloan Digital Sky Survey (SDSS) in the local Universe. This will provide an unparalleled resource to study the physical processes that shape galaxy evolution and will determine the key relations between stellar mass, star-formation, metallicity and the role of feedback. Moreover, MOONS will fill a critical gap in discovery space, unveiling the redshift desert (1.5 < \(z < 3\)), thus enabling studies of this crucial epoch around the peak of star formation, the assembly of the most massive galaxies, the effects of environment on galaxy properties, and the connection with the growth of super-massive black holes.

2.3 Impact of the science cases on the instrument’s design

These science cases impact the design of MOONS in a host of ways, many of which are blindingly obvious, but they shall be referred to repeatedly so are worth noting now:

1. Many objects. The primary limiting factor in this regard is the number of fibers we can pack onto the detectors and the number of detectors we can afford. With ~500 fibers per spectrograph and the étendue of the VLT (see section 5) we still have extremely large optics to handle. This leads to a very large cryostat and very fast cameras to focus the light down onto the detectors. Also, since MOONS will often be used for surveys we have made every effort to ensure that the observing overheads are minimized. This is detailed more in section 6.

2. High sensitivity. Since one of MOONS’s key advantages over similar instruments is the size of its light collecting bucket, we must ensure we do not waste this advantage with a low throughput instrument. At every turn transmission has therefore been prioritized. Likewise the quantum efficiency of the detectors is critical.

3. Excellent sky-subtraction. Perhaps one of the most important aspects of MOONS, is the requirement for excellent sky subtraction. Going after faint objects and doing so in the infrared – where the sky is littered with exceedingly bright OH emission features – is a real challenge. The first impact of this is to ensure that the fibers can be positioned extremely closely together on the sky to allow nearby paired sky observations to be made. Likewise, in order to be able to subtract the sky from one fiber against another, the relative transmission of the fibers must be extremely well known and must be very stable. This has a significant impact on the calibration system and on the performance of key design elements, e.g. the fiber tilt.

2.4 Observing strategy

To aid the description of the instrument that follows it is necessary to briefly describe the observing strategies that MOONS will employ.

1. Stare: In this observing mode the vast majority of fibers will be on targets, with sky fibers distributed across the focal plane. Suitable for bright targets, where a basic median-like sky-subtraction is sufficient.

2. Stare+Node: The majority, if not all fibers will be on targets, and the telescope is then nodded to a nearby sky position. This has the advantage that the sky flux will pass through the same fiber as the target, thus removing many instrumental effects. The quality of the sky-subtraction will depend on the frequency of the sky nods.

3. XSwitch: This provides the most accurate sky-subtraction so will be used with the faintest targets. Here every object fiber will have an adjacent sky fiber at the same fixed distance (<30") away and direction. The telescope is then nodded by the same distance and direction, so that object and sky fibers are reversed. This observing pattern is then reversed. This “A-B-B-A” strategy allows both temporal and spatial sky variation to be removed, as well as accounting for instrumental artifacts. More discussion of this fiendish strategy lies in Rodrigues et al1.
3. INSTRUMENT OVERVIEW

As with many of the other MOS instruments that were highlighted previously, MOONS can be easily broken down into two main sections: the part that is mechanically attached to the telescope and couples the light into the optical fibers and then the static spectrograph wherein the light from the fibers is dispersed and recorded. MOONS differs from many of these other instruments in that it is mounted on the telescope’s Nasmyth port as opposed to sitting at its prime focus. As with many design features this results in a range of pros and cons that we will highlight throughout this paper.

In general ESO operate a clear distinction between the instrument and telescope, with interfaces and processes that have been defined and refined over many years of installing new instruments. As a result, the VLT retains a remarkable high observing efficiency even when new instruments are being installed. For MOONS this has two major impacts on the design and the integration at the telescope. Firstly, MOONS must respect the mass and volume constraints that the VLT’s Nasmyth Platform impose, which also means that it is not possible to add other elements of the instrument elsewhere within the telescope, e.g. we can’t add an inspection camera near the M2 of the telescope that could monitor the alignment of the optical fibers. The second major impact is that ESO require thorough and near-complete testing of the instrument before it is shipped to the VLT, thus massively reducing the instrument’s commissioning time. These two impacts are not disconnected, looking again at the example of the camera for inspecting fibers; if this were an essential part of the instrument, complete testing in the lab would not be possible. MOONS consequently can be thought of as a very self-contained system that sits almost exclusively on the Nasmyth Platform, aside from a few electronic cabinets that are placed elsewhere, who’s location is in no way relevant to performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplex</td>
<td>1001</td>
<td></td>
</tr>
<tr>
<td>Telescope</td>
<td>VLT, 8 m</td>
<td></td>
</tr>
<tr>
<td>Field of view</td>
<td>25 arcmin in diameter</td>
<td>This is using the full fov of the VLT</td>
</tr>
<tr>
<td>On sky aperture of each fiber</td>
<td>1.2”</td>
<td></td>
</tr>
<tr>
<td>Spectral channels</td>
<td>RI, YJ and H band</td>
<td>Observed simultaneously</td>
</tr>
<tr>
<td>Resolution modes</td>
<td>Low and high res</td>
<td>RI and H bands can be switched, while YJ band is fixed resolution</td>
</tr>
<tr>
<td>Low res spectral coverage</td>
<td>0.65 – 1.8 µm</td>
<td>With small atmospheric gap between J and H band</td>
</tr>
<tr>
<td>Low res spectral resolution</td>
<td>R_{RI} &gt; 4100, R_{YJ} &gt; 4300, R_{H} &gt; 6600</td>
<td></td>
</tr>
<tr>
<td>High res spectral coverage</td>
<td>λ_{RI} = 0.76 – 0.89 µm, λ_{YJ} = 0.93 – 1.35µm, λ_{H} = 1.52 – 1.64 µm</td>
<td></td>
</tr>
<tr>
<td>High res spectral resolution</td>
<td>R_{RI} &gt; 9200, R_{YJ} &gt; 4300, R_{H} &gt; 18300</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>&gt; 30% in Low res, &gt;25% in high res</td>
<td>These are average values</td>
</tr>
<tr>
<td>Field coverage</td>
<td>&gt; 3 fibers can reach any point in the focal plane</td>
<td></td>
</tr>
<tr>
<td>Minimum on fiber separation</td>
<td>10”</td>
<td>Closest approach of two fibers cores</td>
</tr>
<tr>
<td>Optimal sky subtraction method</td>
<td>XSwitch</td>
<td>On sky switching of target/sky fiber pairs. See section 2.4.</td>
</tr>
<tr>
<td>Calibration methods</td>
<td>Daytime flat fields, attached flats as part of observations, ThAr lamps for wavelengths</td>
<td>See section 4.6.</td>
</tr>
<tr>
<td>Observing overheads</td>
<td>Fiber positioning time &lt; 2 mins Attached flats + 2 mins</td>
<td>See section 6.</td>
</tr>
<tr>
<td>Predicted sensitivity (low res)</td>
<td>S/N &gt; 5 for AB 20.2 in 1 hour</td>
<td>These sensitivities are based on detailed modeling, but are clearly currently only best estimates.</td>
</tr>
<tr>
<td>Predicted sensitivity (high res)</td>
<td>S/N &gt; 30, for H ~ 15.0 in 1 hour</td>
<td></td>
</tr>
<tr>
<td>Acquisition star limiting mag</td>
<td>V ~ 21 mag</td>
<td>In a 30 second exposure</td>
</tr>
</tbody>
</table>
Figure 2. An annotated image of MOONS that provides an overview of the main sub-systems. The numbering of the boxes indicates the sequence that the elements should be considered and also the order that they are presented within this paper. Obviously the one critical aspect of MOONS that is not shown here is the software.
4. ROTATING FRONT END

This is the part of MOONS that is attached to the telescope and therefore must rotate with it during the course of the night. It is advised to examine Figure 2 before reading these sections.

4.1 Field corrector

The first major component of MOONS is the field corrector. As is detailed below, the FPUs are mounted on the focal plate with each FPU’s primary axis of rotation extremely precisely aligned to the telescope’s chief ray. This is only possible because the field corrector ensures that the exit pupil of the VLT is almost concentric to the focal plane’s curvature – without the field corrector this would not be the case. The corrector has the additional advantage that it reduces the radius of curvature of the focal plane from 2090 mm to 4210 mm; thus making the focal plane closer to a flat surface, which significantly simplifies the assembly of the units on the focal plate – both the back and the front surfaces. The field corrector is shown in left hand panel of Figure 3, and is comprised of plano-convex lens followed by a symmetrical biconcave element. As with nearly all the other transmissive elements in MOONS, these lenses are made of low OH Fused Silica (<10 ppm), which is highly transmissive across the full MOONS wavelength range and by using the low OH version of the glass, does not suffer from any noticeable absorption features. At the time of writing the blanks for the field corrector are complete; the glass for the second element is shown in Figure 3.

Figure 3. LHS: Two-element field corrector design of MOONS. RHS: Recently finished Fused Silica blank for the second element, produced by Heraeus Optics.

4.2 Focal plate

As is indicated in Figure 2, all the Fiber Positioning Units (FPUs), the Acquisition Cameras (ACs) and the fiducials for the metrology cameras are mounted on one monolithic plate. All three of these elements use a common triangular mounting pattern that can be clearly seen in Figure 4. The near 1 m diameter plate therefore has 1069 identical facets; the final system will have 20 ACs and 48 fiducials, leaving 1001 spaces for FPUs.

The chief ray is not perfectly perpendicular to the plate and consequently all 1069 facets have slightly different angles relative to the surface. The error on these facets forms a non-negligible component of the total tilt error allowed on the fiber, which as is discussed later is critical. The final plate shown in Figure 4 was machined by Alimex GmbH in Germany, who have met the individual facet tilt error requirement of <2 arcmins error.

The focal plane of the VLT lies only 114 mm behind the back surface of the field corrector. Therefore it is not possible to view the positioners from within MOONS without retracting the focal plate away from the field corrector. This is done by way of three motorized stages, which drive this 350 kg module away from the forward ‘science’ position back by 450 mm to the ‘metrology’ position. To ensure that there is no misalignment possible one of the motors behaves as the ‘master’ with the other two as ‘slaves’, whose drive signals merely mimic those sent to the master. In the science position the plate is driven against three machined hard stops that critically define the overall plate tilt relative to the optical axis. Note though, the exact lateral position is not critical as the ACs are used for the precise alignment of the plate on sky.
Figure 4. LHS: A CAD rendering of the top side of the focal plate. The purple Beta arms can all be seen in their datum positions, the red circle show the locations of the fiducials used by the metrology cameras to get absolute positional calibration, the black circles show the locations of the Acquisition Cameras, note their spiral pattern. RHS: the real machined focal plate, ready to be populated.

4.3 Fiber Positioning Units (FPUs)

Arguably the most complex element of MOONS is the fiber positioning system. The key design features of the FPUs are shown in Figure 5, while their performance requirements are summarised in Table 2. This paper should be considered the most up to date definition of performance of the FPUs, but a more detailed discussion of their design rationale can be found in a paper from the 2016 SPIE proceedings.

Each FPU has two Faulhaber AM0820 stepper motors, which drive an alpha and beta arm that act like an elbow and shoulder joint to give complete coverage over a small region of the focal plane. Due to the desire for excellent sky-subtraction the MOONS FPUs are able to reach the centre of their neighbouring FPU’s patrol field, thus increasing the density of coverage of the focal plane and increasing the likelihood of being able to align two FPUs close together to allow for an object-sky pairing as discussed in section 2.4. To ensure that the FPUs cannot collide when the beta arm is folded in on itself, the alpha arm is 8mm long and the beta arm is 17mm, which does have the result that an FPU cannot actually reach its own centre.

One of the most challenging design aspects for the FPUs has been the tilt requirement. Each FPU must be aligned with the telescope’s chief ray, even when the arm is fully extended; failure to achieve this requirement would mean that the fiber will not see the full pupil of the telescope. This would lead to a variation in transmission for the fiber that would be extremely difficult to calibrate and would therefore compromise the quality of the sky-subtraction that can be achieved. The tilt error is comprised of three main components: the facet error at the base of the focal plate, the total tilt error of the FPU assembly and the alignment error of the micro-lens to the fiber centre.

The FPUs are being manufactured by the MPS group in Switzerland; by working closely with them and the motor manufacturers Faulhaber, we have been able to meet the remarkably tight tilt tolerance of the FPUs. Various design solutions were explored including external bearings, modified bearings and final solution has been a hybrid of the two where the bearings of the gearbox output shaft have been incorporated within the structure of the FPU itself. Also numerous modifications such as: thicker motor shaft diameters to meet the flexure tolerances, and also a ceramic shaft on the alpha motor that electrically isolates the upper part of the FPU allowing it to be held at fixed voltage, which is necessary for the anti-collision awareness system (see Figure 5).
All this has been achieved whilst also trying to ensure that the effects of Focal Ratio Degradation (FRD) are minimized. Both stress testing of the fibers in free space and lifetime testing with the FPUs has been carried out to monitor whether the repeated twisting of the fibers has any impact on FRD, or indeed whether the interaction of the fiber with the mechanical structure of the FPU damages the fiber in any way. All testing has shown that the effects are minimal – in fact they were below the level we were testing to, so we are satisfied that this has no impact on the design. This potentially influences the calibration strategy, as is discussed in section 6.2.

Table 2. Summary of the main FPU requirements for MOONS. Note that these requirements must be met for all FPUs, i.e. they do not represent acceptable rms errors but rather multi-sigma levels of required precision.

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Y positional accuracy</td>
<td>+/- 20 microns</td>
<td>This is 0.05” on sky. This precision is achieved in open loop, counting steps from the datum switch.</td>
</tr>
<tr>
<td>Tilt error</td>
<td>&lt; 15 arcmin</td>
<td>This is the total tilt error on the fiber and includes contribution from the FPU (&lt;12 arcmin), the focal plate (&lt; 2 arcmin) and the microlens alignment (&lt;6 arcmin).</td>
</tr>
<tr>
<td>Plate pitch</td>
<td>25 mm from the centre of each FPU to its neighbour.</td>
<td>This is defined at the focal plane; the actual spacing on the focal plate is slightly larger due to the plate’s curvature and varies across the surface.</td>
</tr>
<tr>
<td>Overlap</td>
<td>100%</td>
<td>Each FPU can reach its neighbour’s centre.</td>
</tr>
<tr>
<td>Arm lengths</td>
<td>Alpha: 8 mm, Beta: 17 mm</td>
<td></td>
</tr>
<tr>
<td>Positioning time</td>
<td>&lt; 40 seconds</td>
<td>This is not including any analysis of position by the metrology system</td>
</tr>
<tr>
<td>Power consumption</td>
<td>16 Amps for all FPUs</td>
<td>This is the peak possible power consumption</td>
</tr>
<tr>
<td>Number of motions</td>
<td>&gt;100,000</td>
<td>Assuming a 10 year lifetime for the instrument</td>
</tr>
<tr>
<td>Collision awareness</td>
<td>Yes</td>
<td>The beta arms are held at different voltages to electrically identify any collisions that might occur.</td>
</tr>
</tbody>
</table>

Figure 5. Annotated image of a group of MOONS FPUs near-final prototypes mounted in the verification rig.
We are currently setting up a dedicated testing setup for the FPUs. While the FPUs will arrive from the suppliers with basic functionality confirmed, the intention is that a full suite of tests will be carried out to characterize performance for every FPU individually. This verification rig is now complete, but is in a light-tight box, so a CAD drawing of the system is shown in Figure 6. There are many key properties that will need to be individually tested:

- The final tilt of the assembled fiber and FPU will be measured. This will be done by back-illuminating the fiber onto a screen that is four meters away, which is the distance to the pupil in the VLT. As the FPU is rotated the large spot of light illuminating the screen should remain stationary if the fiber is correctly aligned.
- The offset between the metrology targets and the fiber, this must be a three dimensional measurement, so will combine data from two cameras both of which are fitted with calibrated telecentric lenses.
- The length of the FPU arms will be precisely measured and recorded by rotating the FPUs through full rotations to work out the radius of the fiber’s positions, which is the arm length.
- There is a variation in the relationship between number of steps the motor has travelled and the angle the arm will actually turn through. This arises due to imperfections within the gear-head and is unique to every FPU. Tests will be made by repeatedly moving the FPU through fixed numbers of steps and calculating the angular distance travelled. Unlike all the other calibrations, these tests will be repeated periodically at the telescope as it is expected that this relationship could vary during the lifetime of the instrument.

All testing will be automated, allowing up to six FPUs to be tested in a cycle, the intention being that two batches can be tested in a 24 hour window. Even with this automated system it will take over 80 days to fully characterize all the FPUs.

Figure 6. LHS: CAD drawing of the complete FPU Verification rig, showing the full four-meter light path for the alignment tests. RHS: A close up of the real rig showing the multiple cameras used for different tests. Also visible is the rotating platform on which the FPUs are mounted that allows up to six FPUs to be tested in one setup.

4.4 Acquisition Cameras (ACs)

MOONS has 20 ACs distributed across the focal plane that are used for fine alignment of the instrument on sky. Each camera has a fov of 37x37", although only the central 30" diameter is completely unvignetted. The cameras have very few elements and since they sit at the VLT’s focal plane, are extremely sensitive. It is expected that even a 21st magnitude object can be observed in under 30s to the required S/N to allow offset computation. Although the cameras are Peltier cooled, initial on sky testing using a 10 inch telescope, indicates that the noise performance of the cameras is sufficiently low that except for the faintest objects, this cooling will be unnecessary – this is advantageous as it minimizes the power dissipation into the focal plate. The ACs are spaced at different radial distances so that by rotating the instrument effectively the whole fov of the VLT can be used. Detailed sky modeling suggests that there is >99% chance that the observer will be able to identify 3 stars that are brighter than 19th mag, even at high galactic latitudes.
As their name suggests these cameras will not be used for guiding, which is the remit of the VLT Guide Probe, but rather to make any small offsets that might arise due to the plate’s rotation or any mechanical misalignments. Since the cameras have a relatively small field of view, it will not be possible to observe the same guide stars when nodded to the B position in the XSwitch mode. However, it is expected that after returning to the A position, the exact position of the acquisition stars will be checked relative to the original acquisition and again any small offsets will be sent to the telescope. The effects of atmospheric diffraction will be compensated for here too, as the offset will be calculated to a specific central wavelength as requested by the observer – note that the ACs themselves observe in the R band.

Figure 7. LHS: cross section of an Acquisition Camera, showing the relative simplicity of the design that uses only a few lenses to reimagine a portion of the VLT field of view onto the cooled detector, thus giving a high transmission. RHS: A prototype acquisition camera mounted next to a prototype FPU.

4.5 Metrology Cameras

The metrology cameras monitor the precise positioning of the FPUs when the plate is retracted. They are capable of measuring the location of an FPU to <15 microns. There are 12 cameras mounted around the edge of the field corrector each of which can see a section of the field plate, see Figure 8. These cameras are highly off-axis, so already view a significant depth of field – it would therefore not be possible to view the full focal plate with fewer cameras. A fuller discussion of the metrology camera can be found in the 2016 SPIE proceedings9.

Due to the off-axis location of the cameras it would not be possible to view any light exiting the fibers even if they could be back-illuminated. Instead each FPU has a metrology target mounted on the Beta arm, this can be seen in Figure 8. The two circular discs are made of the ceramic MACOR, which delivers a diffuse reflection that is invariant of the location of the light source10. The focal plate is illuminated by a set of lamps around the edge of the plate. The light reflected from the metrology targets is then identified using the astronomical software Source-Extractor11, which allows quick filtering of the results to reject any scattered light artifacts. The software is used in two different modes, a ‘guided’ search, where the position of the FPU is roughly predicted, and so only small regions of the metrology images have to be searched; and a ‘blind’ search where no prior knowledge of position is given. For this blind search each FPU can be uniquely identified by the orientation of the arm relative to the pre-known centers of the FPU patrol fields – here the different spot sizes aid orientation determination. The guided search can locate all the FPUs in less than 30 seconds, whereas the blind search is slower – however, this mode will likely only be used in the event of recovery from a power failure.

As can be seen in Figure 8, every camera can see 13 different fiducial markers. These are at fixed positions across the plate that will have been measured to very high precision during integration. Many of the fiducials and ~80% of the FPUs can be seen by multiple cameras, thus increasing the precision of the individual measurements and ensuring accurate measurements across the whole plate. The plate is also fitted with thirteen temperature sensors to allow any corrections for plate expansion/contraction to be made. Note that the fiducials and the guide cameras are all shorter than the FPUs, which allows the FPUs to move over the top of them without any restrictions. This does not effect the metrology measurements as the fiducials are large, with many spots and not all the fiducial need to be seen all the time for every measurement.
The metrology is critical for defining the datum position, for calibrating the behaviour of the FPUs in the instrument and for recovering from problems, e.g. power failures. As is detailed in section 6, during normal operation the expectation is that we will generally use the metrology system while a flat is taken or when requested by the astronomer. For small movement and movements starting from datum the FPUs have such precise gearheads and such well-defined datum positions that it should be possible to perform observations without relying on the cameras; since this means that the plate does not have to be retracted to make measurements, it significantly increases the observing efficiency.

![Figure 8. LHS: each green trapezium represents the field of view of one metrology camera on the focal plate. The red circles show fiducials used to give calibration of the exact plate scale and overlap between the cameras. As can be seen, all cameras can measure the central fiducial simultaneously. RHS: the image from the verification rig of the beta arm of an FPU. The back-illuminated fiber can be seen adjacent to the two circular MACOR metrology target spots.]

4.6 Calibration Unit

The MOONS calibration unit provides both flat fielding and wavelength calibration for all the fibers. Behind the field corrector are two sliding doors that can be closed to form a 880 mm diameter screen that is visible to all the FPUs. This screen is coated in a Lambertian diffuser, which provides uniform reflectivity. Onto this surface the different lamps are projected, as can be seen Figure 9. When the focal plate is retracted, into its calibration position, each of the fibers will receive flux from an effective 30 mm diameter region of the screen’s surface.

To ensure excellent sky-subtraction it is critical that the relative transmission of all the fibers is known to better than 1% and to achieve this the spatial variation of the flux across the calibration screen must also be equally flat. Note though that this flatness is only required over the 30 mm scale-lengths viewed by each fiber, which greatly simplifies the flatness requirement. To achieve this level of flatness MOONS is using a spatially uniform light source.

One of the beauties of this system is that flat fields can be taken for the FPUs once they are in their observing positions. As was indicated earlier, testing indicates that moving the fibers to different locations doesn’t induce any measureable FRD effects, however, if in the real instrument or if after a significant length of time, this became a problem, it would be possible to determine the exact transmission of each fiber in its actual observing position through this attached flat fielding technique.

The calibration system will only provide relative transmission of the fibers; it will be necessary to combine this with real observations to obtain absolute transmission values. Also there is variation in transmission across the field of view that is caused by telescope vignetting effects. MOONS will compensate for this effect, using the ACs that are distributed across the focal plate. These can also be flat fielded using the calibration system and then compared to on-sky observations, thus allowing a transmission profile across the focal plate to be determined.
Figure 9. LHS: the projected light cones for the two wavelength calibration lamps that fill the circular calibration screen, note the these are highly off-axis. RHS: the parts for the flat-field projection system that will be used to deliver a field that is spatially flat to <1% across the whole calibration screen.

5. SPECTROGRAPH

5.1 Cryostat

Put simply, the MOONS cryostat is large, as can be seen from Figure 2. It measures over 4.5 x 2.5 x 2.7 metres and will weigh just over 7 tonnes, which is close to the limit that can be placed on the VLT Nasmyth Platform during normal operations. The two triple-arm spectrographs are mounted on a central vertical optical bench, whose natural symmetry reduces stresses within the system. The cryostat has a central section that surrounds the optical bench and on either side of this are two large doors covering each of the two spectrographs - Figure 2 shows one of these doors removed. The whole door must be removed to allow access to the spectrograph optics, but the majority of the services (e.g. coolers and detector controllers) and the fibers themselves all pass through the static central section, and so do not have to be removed during normal maintenance. Also visible in Figure 2 is the large flat brace that connects the top of the cryostat to the telescope, this is there to improve vibrational stability during an earthquake.

Figure 10. The MOONS optical design, shown in high-resolution mode. The blue dotted circles indicate the two prism-disperser-prism combinations that are moved in and out of the beam to switch between high and low resolution modes. The RI and H channels resemble the YJ layout when in low-res mode, with only a single dispersing element in the beam.
5.2 Optical design

Many of the properties of the optical design for the triple arm spectrographs are detailed in Figure 2 and in the following discussion. The following aspects are also of note but are not detailed elsewhere:

- The collimator is f/3.5 and is marginally oversized to accommodate any misalignments of fibers in the slit.
- MOONS will use 158 micron diameter fibers. This was chosen as a trade off between the optimal resolution of the detector and the tolerance to allowed tilt in the FPU.
- 3 mm thick band-pass filters are used in the R1 and YJ cameras, placed between L2 of the camera and the detector surface itself. In the H band cameras, a 0.3 mm thick piece of silicon is at the same location. These are used to block any second order features and to block any light that leaks through the dichroics.
- Each of the two MOONS spectrographs has 5 dispersers, 3 low-res and 2 high-res. The two triple-arm spectrographs are mounted literally back-to-back on the optical bench, which makes it possible to switch between the high and low resolution modes in the RI-band using a single common linear mechanism that passes straight through the optical bench. Likewise, the same is done for the H-band.
- The dichroics are being manufactured by Materion: they are double sided designs with a reflective front surface that selectively reflects shorter wavelength light into the camera, while on the rear surface there is a blocking coating that reduces transmission of any unwanted flux that may have passed through the first surface.

5.3 Slit design

Each spectrograph has a slit comprised of 32 slitlets, each of which contains 16 fibers – although note that not all the fibers in the slit are connected to FPUs (there are 1024 fibers in the two slits, but 1001 FPUs), which allows some flexibility matching FPUs to slitlets. These slitlets have a V-groove profile into which the fibers are laid before being secured with a flat substrate that is fastened on top of them. Various prototypes have been tried, using different materials: the final slitlets are manufactured from wire-eroded Invar. This minimizes the FRD effects when the slitlet is cooled, which was a significant difficulty with some of the earlier prototypes. The front surface of the slitlets is polished once the fibers have been bonded in place, which ensures that the tilt alignment is < 0.3 mrad. Detailed TracePro modeling of the scattered light has shown that a significant ghost could potentially be created by light reflecting of the detector surface all the way back through the instrument and then back off the polished slit. We have investigated numerous ways to reduce this effect, e.g. blackening the slit or placing a darkened strip along the length of the collimator mirror, but the preferred solution is to place a metal mask in front of the slit, this is both blackened to reduce reflection and more importantly angled to send the reflected image out of the beam.

It is possible to move the entire slit block of MOONS by 200 µm, which represents half the fiber separation. This makes it possible to move the imaged fibers on the detector so that they fall on the previously un-illuminated inter-fiber regions. The exact way this will be used in the instrument will depend on the performance of the detectors. The baseline is to switch between these two positions for different exposures; this would assist in the removal of any fixed detector artifacts, such as bad pixels. Alternatively the low-res observations could be taken in one slit position and the high-res in the other. In the first option, the location of bright skylines in one resolution setting could potentially fall in continuum regions in the other setting, and potentially contaminate them through persistence effects in the detector. Such a problem would be removed with second option. This will be investigated and determined once the instrument is complete.

5.4 Cameras

Due to the large number of fibers and size of the available detectors MOONS requires fast, large optics: all the spectral channels consequently use similar f/0.95 Schmidt cameras. A detailed trade off was previously made to consider the benefits of refractive designs, but it was found that due to the number of surfaces and the transmission of the thick optics that were required, the transmission for the Schmidt design is not much lower, despite its ~22% central obscuration. The exact details of the MOONS cameras and their expected optical performance can be found elsewhere12.
One of the critical features of the camera design is that the field lens that lies immediately in front of the detector is glued into a recess within the square hole cut into the first lens in the camera, as can be seen in Figure 11. A full prototype of this L1/L2 lens assembly has been made by Winlight, this uses the correct thickness and curvature for the lenses, this can be seen in Figure 12. This prototype has been cryo-tested by lowering it slowly into liquid nitrogen vapours. The temperature of the central optic was monitored throughout, to ensure the final operating temperature of MOONS was reached. The surface form of the mirrors was monitored with an interferometer throughout the cycle. As can be seen in Figure 12 the fringe patterns are constant before and after cooling, which indicates that there was no deformation of the assembly during cool down. Likewise a full inspection after cooling indicated that there had been no change in the assembly. Since this was a more aggressive cool down than will happen in the real cryostat, it demonstrates that this assembly is a success and we can retire the risk that was associated with it.

A significant advantage of the MOONS cameras is that they effectively only have two separate elements to align: the L1/L2 assembly and the mirror cell. The optical layout of the alignment optics is shown in Figure 13. As can be seen, this makes use of the collimators from the MOONS spectrograph to deliver a collimated beam into the cameras. The beam is folded as shown so that the whole system can be installed within a smaller, conventional cryostat that has been manufactured for testing cryogenic instrument sub-assemblies. The cameras are initially aligned warm and then the whole test assembly is inserted into the cryostat for final cold alignment followed by thermal cycling to demonstrate acceptable alignment stability.

Figure 11. LHS: optical design of a MOONS camera, showing how L1 is mounted within L2. RHS: the mechanical assembly of the camera. The detector adjustment module on the left is mounted in front of the L1 lens mount.

Figure 12. 1: Full size prototype of the L1/L2 assembly. 2: Interferometer measurements of the assembly prior to cool down. 3: Similar measurements of the assembly after cool down, showing minimal changes. The temperature probe mounted to the centre of the assembly can be seen in the interferometer images.
A set of fibers are mounted in the slit position to deliver a collimated beam to the camera, these fibers are then imaged by the MOONS camera onto the focal plane. Here a small inspection sensor mounted on a three-axis stage is used to examine intra- and extra-focal plane Hartmann images and determine any residual misalignments in the camera system. The M1 cell of the camera is mounted on three cryogenic motors that can be used to adjust the relative spacing of the mirror to the L1/L2 assembly. These will have been set correct to the de-space change between warm and cold and are used to make small changes to de-space and tilt. Once aligned in the test cryostat the intention is that these motors will be removed from the alignment mechanism and fitted to the next camera assembly to be aligned.

The actual detector of MOONS will sit in the Detector Adjustment Module (DAM) that is mounted on the front of the camera – as can be seen in Figure 11. The DAM is attached to the cameras by an adjustment ring that has three actuated points, allowing the tip, tilt and piston effects to be corrected for when the final detector is installed in the instrument. The motors driving the DAM will be permanently attached, so it will always be possible to adjust the focus of the MOONS cameras if needed.

![Figure 13](image)

Figure 13. LHS: the layout for the camera alignment. RHS: the cad model showing the major elements of the camera alignment assembly mounted on a purpose-built optical bench, which can be loaded into the test cryostat on a rail system.

### 5.5 Detectors

Each of the three cameras in MOONS will use a 4K x 4K array that is mounted behind the field corrector lens. The two infra-red channels will exploit the new Hawaii 4RGs from Teledyne, which are described in greater detail in many papers\(^\text{13}\). MOONS will use the 2.5 μm cut-off, which is technically longer than is required but this maximises the QE over the MOONS wavelength range, although it does require the optical bench to be cooled to a lower temperature. Due to the speed of the cameras, light is incident on the edge of the detector at angles of up to 60 degrees; as a consequence of this MOONS will use an anti-reflection coating that is optimised for such extreme angles. This coating does not yield the lowest possible reflectance for light perpendicular to the detector surface, but gives the best overall performance.

In the IR channel MOONS will use fully-depleted detectors that have been developed by Lawrence Berkeley National Laboratories (LBNL) – see acknowledgements. These devices give considerably higher QE beyond 0.9 μm than any other currently available 4K x 4K device and have been developed by LBNL for the DESI project\(^\text{14}\).

All the detectors are mounted in a common design for the DAM, as described previously. Packing the detectors and their readout electronics into so small a volume as been a significant challenge, especially for the 64 channel output of the 4RGs, where three packed boards of pre-amplifiers have been included, all the while minimizing the possible cross-talk that could occur between those boards.
6. OBSERVING

One aspect where MOONS is significantly different from the other MOS instruments described in the opening of this paper, is that it will be offered to the ESO community as ‘normal’ VLT instrument, where observers can propose to use the instrument for anything they can imagine. This has had some impacts on the way the observations will be executed and therefore in the way the instrument has been designed.

6.1 Observing strategies

ESO breaks observations into structures called Observations Blocks (OBs); these are entirely independent and in principle can be called in any sequence. The OB will often be made up of two different templates, one for ‘acquisition’, which is the setup of the instrument and telescope, and the other for the observations. Figure 14 shows the different possible setup options that are possible with MOONS, the final part of the figure labeled “Take data” would follow a range of different options that are not explored further here, but would basically define the exposure times for the different channels and the nodding frequency to sky positions.

As is discussed more in the next section, in general the FPUs will be run from their datum position to the science position to aid path planning. However, looking at Figure 14, it can be seen that the first question is how far the FPUs currently are from their desired observing location? If the OB is a repeat of the previous observation, then this distance will be minimal, perhaps only a few steps will be required by some FPUs to correct for slight differences in position due to the change in hour angle and therefore atmospheric refraction. If this is the case, then the FPUs will not return to datum before beginning the next observation (option A in Figure 14), otherwise the FPUs will return to datum by reversing the last motions they made. Whilst this is happening the waveforms for the new observation will be calculated. The subsequent sequence of events depends on whether the metrology is requested or not (options C and B respectively) or whether the astronomer has requested an attached flat (option D).

Figure 14. The basic steps executed at the start of a MOONS OB to set up the instrument. There are four options to set up the instrument, with significantly different setup times. The relative vertical size of the boxes indicates relative time to execute a function. Blue boxes indicate FPU movements; light grey boxes plate movements; purple boxes are calculations/measurements; green boxes are on-sky and telescope operations, and red signify taking data.
The relative vertical height of the boxes in Figure 14 are loosely meant to indicate the relative duration of different activities. As a guide, the minimum telescope present time for VLT that can be assumed when planning observations in advance is 6 minutes. It is expected that even option D could be executed in this time frame. However, in reality when at the telescope, the telescope present time can be much less than this 6 minute window (e.g. if fields are close together on the sky) and so there are significant advantages of using option B to reduce overheads down to only a few minutes.

6.2 Path Planning

The overlap of the FPU patrol fields ensures good coverage of the focal plane, but it does present the problem that the FPUs have a high chance of colliding. It is therefore critical to fully simulate the motion of the FPUs so that their path can be fully navigated in advance. To do this a routine has been developed that takes advantage of a potential field based approach where FPUs are attracted to their target locations and repulsed by the surrounding FPUs\(^\text{15}\). This allows FPUs to navigate paths around each other, and even around obstacles such a broken FPU.

In principle the quickest observing strategy would be to move the FPUs from configuration A, to configuration B and onto C etc, without any need to return home to datum. However, with this degree of overlap, it is not possible for every FPU to reach its desired target and so the final set of targets that can be reached might depend on the previous configuration. This would not match with ESO’s philosophy of creating OBs in advance that can be executed independently and in any order. So the decision has been made to always simulated paths from the datum position out to the desired science configuration, therefore always ensuring the objects that the astronomer plans to observe when they prepare their observations in advance will be the ones observed at the telescope.

MOONS employs a two-phase approach to ensure that the highest numbers of FPUs can reach their desired science targets – i.e. to get the highest allocation efficiency:

1. First the FPUs are assigned targets by the Observation Preparation Software (OPS). This software first determines which FPUs can reach a particular target and then performs an assignment that ensures that the chosen FPU to target combination will block as few other science targets as possible – i.e. a simple check that the positioned FPU will not directly lie over another science target. In the event that more that one FPU can safely reach a target the OPS also does a check that tries to choose assignment based on a set of selection parameters. These parameters are designed to minimize the degree of ‘difficulty’ for the FPU to reach a target; these include minimizing the distance the motors move or reducing the close approach of FPU patrol fields. The relative significance of the parameters can be differently weighted, thus allowing an optimum assignment of FPUs. In addition to this, the way the MOONS FPUs move gives a ‘handedness’ to the FPU-target assignment, as the target can often be reached by two symmetric alpha and beta arm angle combinations. This handedness gives another free parameter to reduce the degree of difficulty.

2. The output from the OPS is then passed to the path-planning algorithm. This splits the motion of the all the FPUs into 256 time steps. At each time step the FPU moves a small distance along its surrounding potential field, which if unrestricted will lead directly to its assigned target. All the FPUs move at the same time thereby allowing their interaction to be monitored at every time step. Once the motion is complete the full ‘waveform’ of motions is created and downloaded to the FPU ready for execution.

The path analysis routines are still evolving. For Stare observations where the targets are well distribute across the field, the allocation efficiencies that can be achieved are in excess of 95%. However, for XSwitch observations when positions have to come very close together to form sky-object pairs (see Figure 15), the allocation efficiency is seen to drop to nearer 80%. This arises from the strength of the repulsive fields used in the path-planning algorithm, which by design makes the close approach of FPUs difficult. The efficiency has been improved by using a ‘direct move’ system, whereby the FPU is forced to move towards its target, with the repulsion turned off, but collisions are obviously still monitored. Ongoing work is being done to improve this efficiency further.
Figure 15. A screen shot from the path planning simulations, this is mid-motion to highlight various aspects of the simulation. This is an XSwitch observation: notice the pairs of spots indicating object and sky fiber pairs that are all 10” apart and in the same orientation. Spots that will be reached by an FPU are green, while red spots indicate targets that will not be reached. The thick bars indicate the FPUs; blue will reach their target, yellow will not and grey are unassigned. The straight thin grey lines connecting pairs of FPU centres show the location of FPUs that will form an object and sky pair, some of which are out of sight here. Finally the gaps in the grid of FPUs correspond to ACs or fiducials.

6.3 Transmission

Obviously the transmission of the instrument is one of its key properties. The best estimates currently available for the different channels are shown in Figure 16. Much of the data used to generate this figure is from data provided by suppliers for various components, so are relatively robust. However, some aspects are harder to quantify, e.g. the FRD effects in the fibers or losses at the fiber connector. Here we relied on testing and occasionally data form the literature to estimate the transmission. Obviously it is clear that the high-resolution modes have lower transmission, which is partially the result of having two additional prisms in the optical path, but is mainly due to the increased angle of incidence of light onto the dispersive elements. This is necessary to achieve the higher resolution, but reduces the transmission significantly.

Figure 16. The currently predicted transmission for the different MOONS channels, both low and high resolution (HR).
7. CONCLUSION

MOONS is on the way. The designs for nearly all aspects of the instrument are complete and the majority of the large items have been ordered. Over the coming year many of these parts will be delivered and integration of the instrument will begin in earnest. The expectation is that by the end of 2018 much of the cryostat infrastructure will be complete, the first batch of FPUs will be undergoing full characterization, and the first camera will be beginning alignment. These are all major milestones on the road to completing this project by the end of 2020 to eventually make Figure 17 a reality.

![Figure 17. MOONS as it will hopefully look when installed at the VLT in a few years time.](image)

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