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Ground Calibration of the Ariel Space Telescope: Optical Ground Support Equipment design and description.

Neil E. Bowles*[a], Manuel Abreu[b], Tim A. van Kempen[c], Matthijs Krijger[d], Robert Spry[a], Rory Evans[a], Robert A. Watkins[a], Cédric Pereira[b], E.Pascale[e], Paul Eccleston[f], Christopher Pearson[f], Lucile Desjonquères[f], Georgia Bishop[f], Andrew Caldwell[f], Andrea Moneti[g], Mauro Focardi[h], Subhajit Sarkar[i], Giuseppe Malaguti[j], Ioannis Argyriou[k], Keith Nowicki[a], Alexandre Cabral[b], Giovanna Tinetti[l]

[a]Department of Physics, University of Oxford, Parks Road, UK; [b]Institute of Astrophysics and Space Sciences, University of Lisbon, Portugal; [c]SRON Netherlands Institute for Space Research, 2333 CA Lieden, Netherlands; [d]Earth Space Solutions, Netherlands; [e]Sapienza Univer. Di Roma, Italy; [f]RAL Space, STFC Rutherford Appleton Laboratory, UK; [g]Institut d'Astrophysique de Paris, France; [h]INAF, Obsservartorio Astrofisico di Arcetri, Italy; [i]Department of Physics and Astronomy, University of Cardiff, UK; [j]INAF – Osservatorio di Astrofisica e Scienza dello Spazio, Italy; [k]Institute of Astronomy, KU Leuven, Belgium; Department of Physics and Astronomy, University College London, UK.

ABSTRACT

This paper describes the Optical Ground Support Equipment (OGSE) that is being developed for the payload level testing of the Ariel Space Telescope. Ariel has been adopted as ESA's "M4" mission in its Cosmic Visions Programme and will launch in 2029 to the second Earth-Sun Lagrange point. During four years of operation the Ariel payload (PL – the cryogenic payload module plus warm units) will perform precise transit spectroscopy of approximately 1000 known exoplanetary atmospheres using a 1.1 m x 0.7 m telescope coupled to two instruments: the Fine Guidance Sensor (FGS) and the Ariel Infrared Spectrometer (AIRS). These instruments provide three spectrometric channels that cover 1.0 to 7.8 µm wavelength range and three photometric channels between 0.5 and 1.1 µm. The Ariel OGSE will verify the optical and radiometric performance of the integrated Ariel PL under vacuum and cryogenic (<40 K) test conditions within the limitations of operation under Earth's gravity and vibration environments.

To achieve these verification requirements the OGSE is integrated with the main Ariel ground test 5 m thermal vacuum chamber. The test chamber contains a cryogenic enclosure (the Cryogenic Test Rig) that surrounds the PL and the OGSE itself comprises of four subsystems. (1) A cryogenic vacuum chamber and integrating sphere illumination module that is fed by visible, near infrared and thermal infrared sources. The illumination module is mounted external to the Ariel test chamber and coupled via a vacuum feedthrough that relays a 22 mm diameter test beam into the Cryogenic Test Rig. The test beam is then relayed using (2) an injection module that steers the beam to maintain alignment during cool-down and scan the Ariel telescope field of view. The beam is then expanded to partially illuminate the Ariel telescope primary mirror using an (3) ~0.3 m diameter target projector collimating mirror. The final optical component of the OGSE is a (4) beam expander placed on the Ariel common optical bench to compensate for the sub-aperture illumination of the primary and to ensure that the spectrometer modules provide illumination with correct cone angles during ground testing.

It is planned to use the OGSE in 2026 for a full range of calibration and verification tests of the end-to-end telescope and instrument performance, including detectors, field of view and alignment. These tests will then ensure that Ariel meets it challenging photometric and spectral performance requirements.

Keywords: Ariel, Ground calibration, Infrared, Space Telescope, Optical Ground Support Equipment (OGSE), Exoplanets

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1. INTRODUCTION

This paper describes the Optical Ground Support Equipment (OGSE) that is being developed for the payload module (PLM) level testing of the Ariel Space Telescope [1] The PLM contains the integrated telescope, spectrometers and radiators that will then be attached to the Service Module (SM) and is due to be tested using the 5 m vacuum calibration test facilities at STFC RAL Space in the UK.

The OGSE is designed to provide verification of Ariel's science requirements ([2] Table 1) during ground testing as an integrated payload module, as far as is possible given the limitations of operation in a terrestrial thermal vacuum chamber.

Table 1. Ariel Top Level Science Requirements

Ariel Top-level Science Requirement	**Value**
Stability	<100 ppm over 10 hours
Wavelength range	0.5 to 7.8 μm
Visible and infrared Photometer	0.5-0.6 μm, 0.6-0.8 μm, 0.8-1.1 μm
Near-IR spectrometer	NIRSpec 1.2 – 1.95 μm, Resolving power >10
IR Spectrometer	AIRS: 1.95 - 7.8 μm, Resolving power 30 – 100
Payload operating temperature	~55 K passively cooled by a series of V-grooves.
AIRS detector temperature	<42 K, cooled via active Neon Joule-Thompson cooler.

The OGSE is designed to be operated with the Cryo Test Rig (CTR) in the 5 m chamber at RAL Space and consists of (*Figure 1*):

- An Illumination Module as an independent separable vacuum enclosure to provide a stable uniform source of known radiance and spectrum, with optics to pass a collimated test beam into the CTR. This includes the necessary vacuum, cooling systems for thermal background control and visible, near-IR and thermal-IR sources to cover the Ariel spectral range (0.5 to 8 μm).
- An Injection module for transferring the beam from the collimated output of the illumination module to the target projector common optics. The beam is steered before entering the target projector to scan the Ariel focal plane.
- A Target projector to expand the beam from the injection module to partially illuminate the Ariel M1 primary mirror. The Ariel OGSE target projector has an elliptical beam 0.275 x 0.175 m compared to the 1.1 x 0.7 m of the M1 mirror.
- A beam expander module that sits after the exit pupil of the Ariel afocal telescope on the common optics bench. The beam expander ensures that the sub-aperture beam provided by the target projector fills the exit pupil of the system, simulating a telescope with full aperture illumination for the instrumentation on the common optics bench.

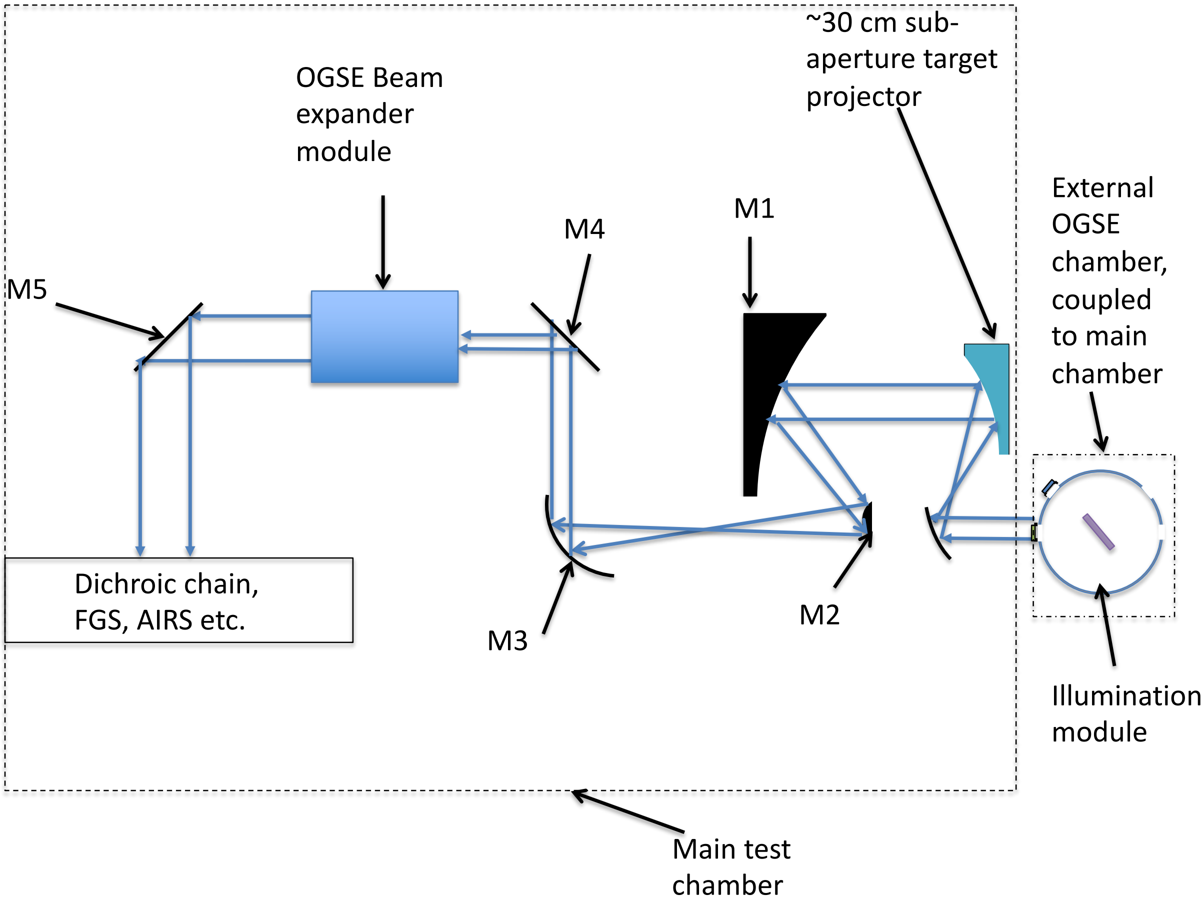

Figure 1. OGSE conceptual layout showing the major sub-systems with the main mirrors of the Ariel telescope and common optics labelled M1-M5.

Since the Ariel instruments require a very high photometric stability (<100 ppm over 10 hours, Table 1) during its operation in a thermally stable environment at the Earth-Sun L2 position, the OGSE must meet several challenging requirements:

1. Ability to monitor and detrend the test illumination signal to level of 10s of ppm.hour$^{1/2}$.
2. Operated at cryogenic temperatures (<70 K) to allow verification of the Ariel AIRS channel 1 dark current (1/e/pix/s).
3. Wide spectral coverage from 0.5 to 8 μm.
4. Well characterized visible and thermal sources that are compatible with the Ariel pipeline detrending requirements [3].
5. A point source output that is capable of producing stellar-like fluxes (as measured at Ariel's primary mirror) through a 50 μm pinhole to enable a representative flux, spot size and spectra on the focal plane._
6. A extended field of view output from the integrtating sphere, designed to have better than 0.5% uniformity for flat field testing._
7. 300x dynamic range in flux to enable testing of both bright (e.g. HD219134 and faint targets (GJ1214).
8. Broad band and spectroscopic illumination sources to test spectral and broadband response of the payload.

Each of the OGSE sub-systems have been designed to support testing and verification of the Ariel payload and are outlined below.

2. ARIEL OPTICAL GROUND SUPPORT EQUIPMENT SUBSYSTEMS

2.1 The Cryogenic Test Rig (CTR)

Although not part of the optical test setup for Ariel the Cryogenic Test Rig (CTR) has the vital function of enclosing and passively cooling the Ariel PLM to its operating temperature of <55 K. The CTR uses a trolley (Figure 2) to mount the Ariel PLM and allows integration and alignment of the test equipment outside the main chamber. The OGSE test beam is passed into the chamber through a window-less vacuum gate valve attached to the main vacuum chamber door (Figure 3).

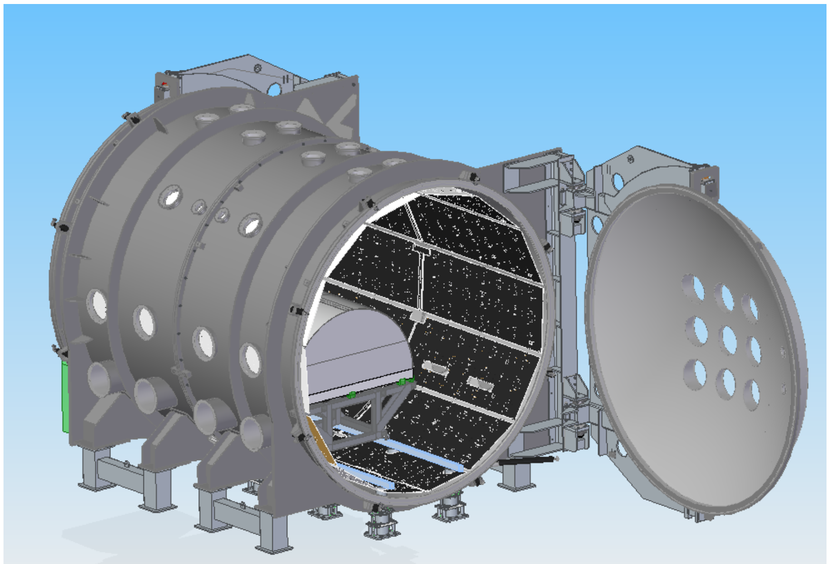

Figure 2. RAL Space 5 m facility with the Cryogenic Test Rig thermal test enclosure, OGSE illuminator module will be mounted on the chamber door.

2.2 Illumination module

The OGSE illumination module is a separate vacuum chamber mounted externally to the main Ariel test chamber. A gate valve can be used to isolate the illumination module from the 5m chamber allowing independent evacuation and cooldown. The support structure of the illumination module is mounted on the vibration isolated seismic block that runs under the 5m chamber, and which is used for the rails that support the CTR independently from the chamber itself. The OGSE support structure and internal optical bench with the necessary sources and transfer optics is thus fixed in inertial space relative to the CTR. To prevent vibrations transferring from the CTR cryocoolers mounted to the same door as the illumination module, the OGSE chamber is vibration isolated from the illumination module support structure. Vibration isolation performance is defined in terms of the end to end pointing between the OGSE and the payload during ground testing. This is tocontrol pointing jitter with implications for broadening of the radius of encircled energy at the Ariel payload module’s detectors.

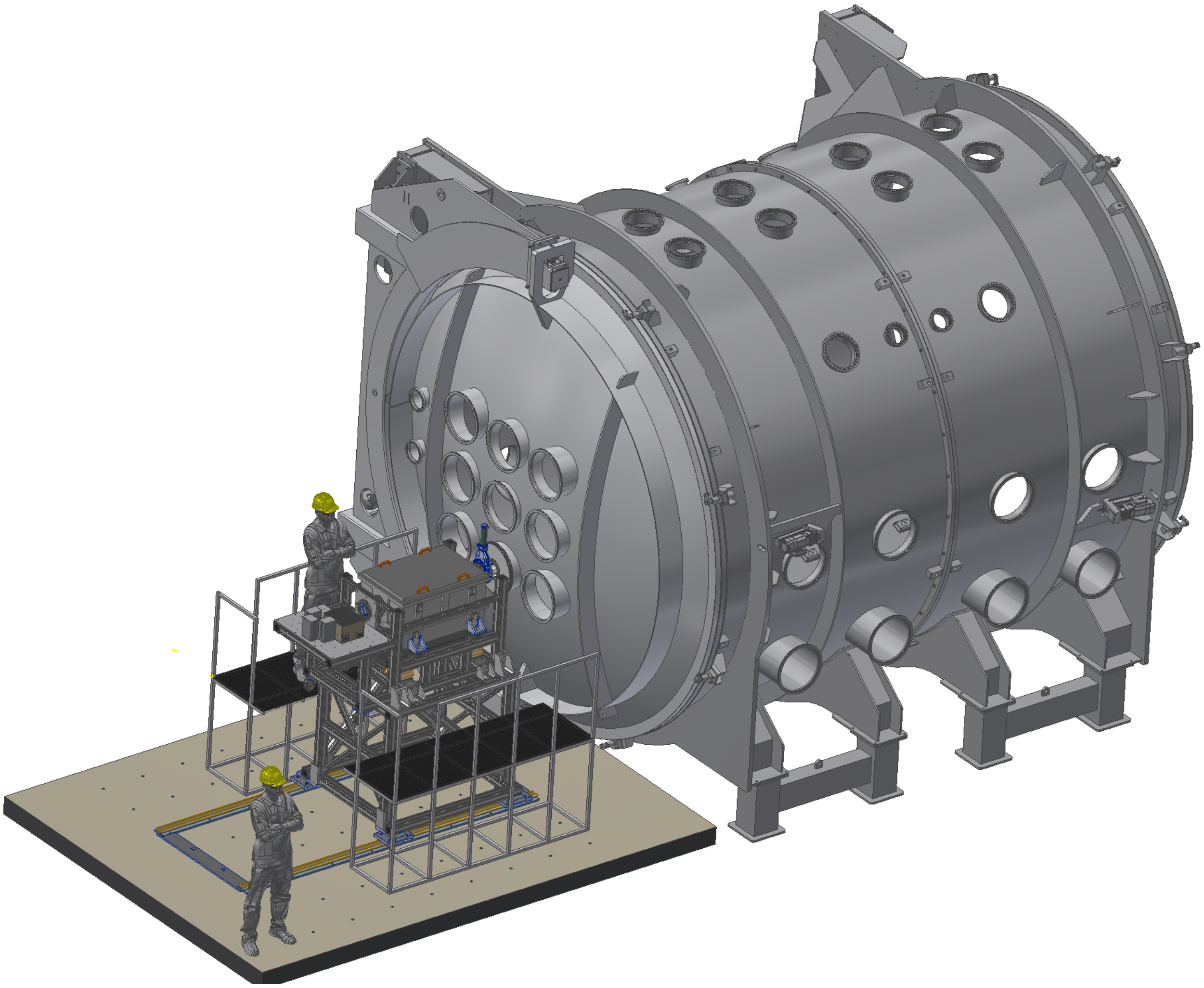

Figure 3. Ariel Illumination vacuum enclosure showing bellows attachment, gantry and gate valve to inject the OGSE test beam into the Ariel test chamber.

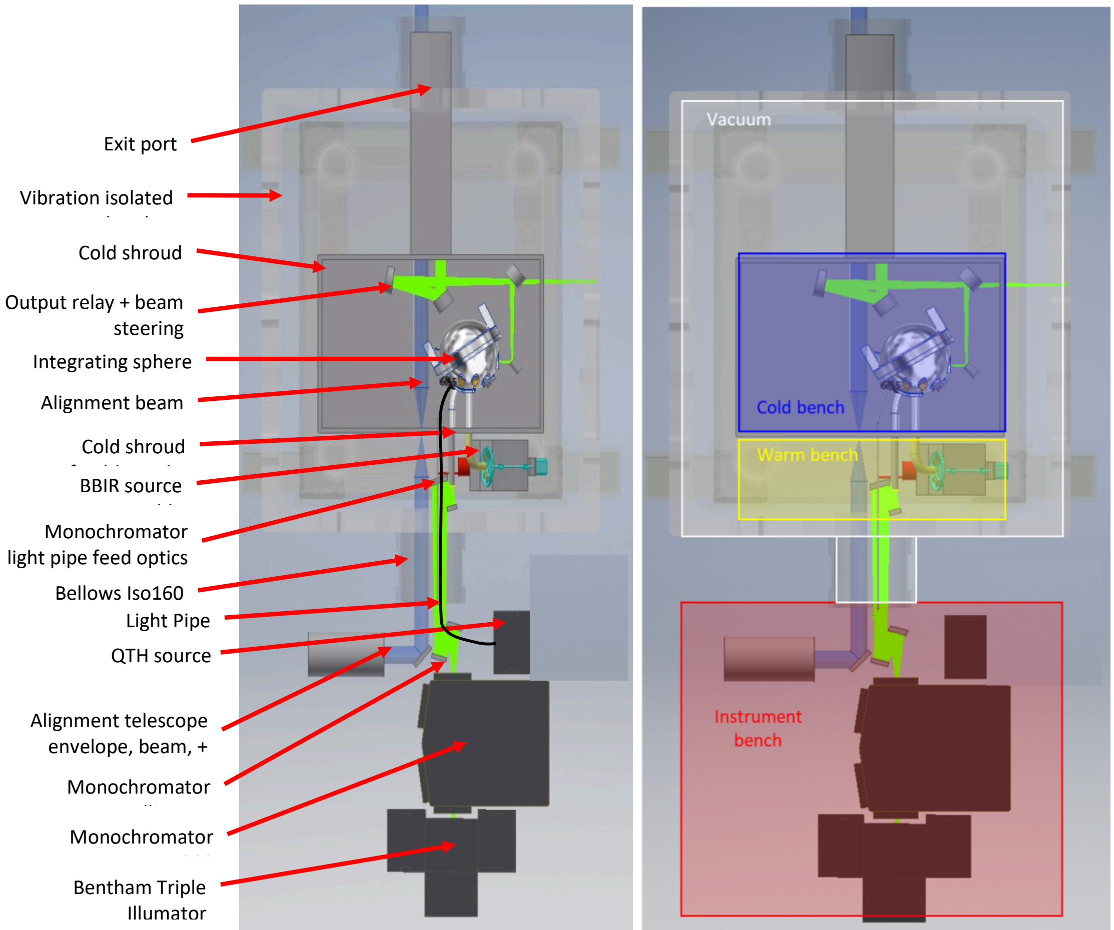

Figure 4. Internal layout of the illumination module with temperature zones shown.

Within the illumination module a diffuse gold coated integrating sphere (Figure 5) is used to generate a Lambertian, spatially uniform (<0.5% variation) flux from several sources covering the Ariel wavelength range (Table 1). The integrating sphere is cooled (~70K) to reduce the thermal background contribution using a radiative heater exchanger connected to a vibration isolated single stage cold head. A cold (~70 K) pinhole assembly mounted at the sphere output provides a point source field, which is collimated by an off axis parabolic mirror. The collimated beam pupil is defined by the injection module optics to an ellipse with 22 mm major axis diameter, giving an f number of 24 at the point source (geometric average of major and minor directions).

Reference detectors, mounted on additional output ports, are used to measure, and allow correction for source stability. The current baseline detectors are single element InGaAs for the visible and near-IR, InSb for the 1- 5 µm range and Mercury Cadmium Telluride (MCT) for wavelengths to 8 µm.

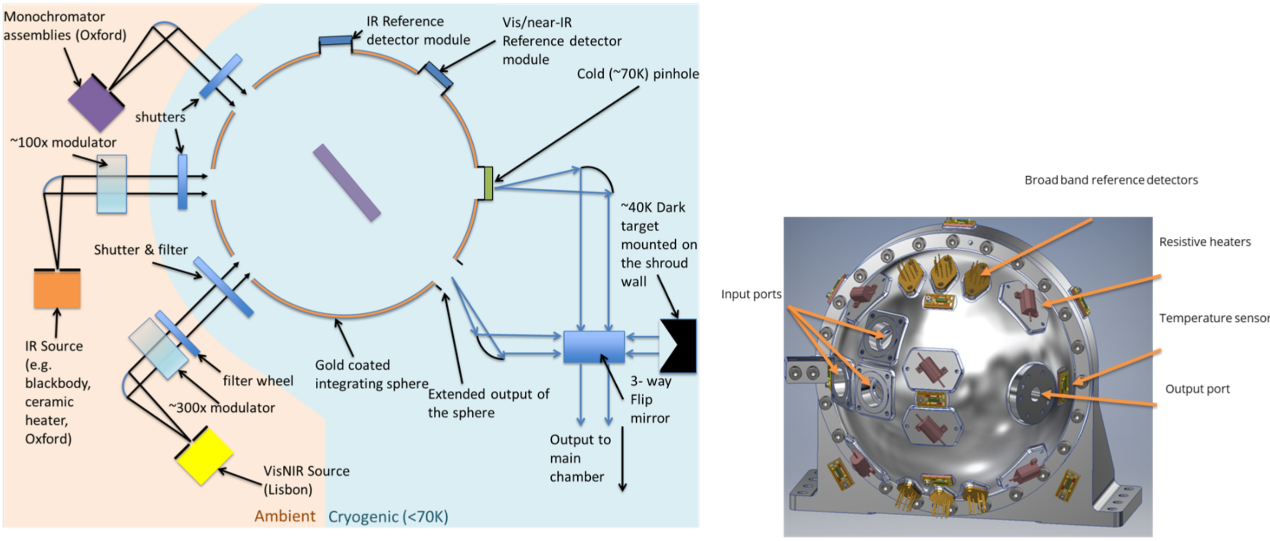

Figure 5. Conceptual design (not to scale, left) for the Illumination module, based on a visible and IR source plus monochromator for spectral performance, integrating sphere, reference detectors for output-level monitoring and scannable exit port. Illumination Module CAD design (right) for a 150 mm diameter sphere.

Two stabilized broadband sources are used, a ceramic coated silicon carbide heater for wavelengths >2.0 µm and a visible/near-IR source (quartz halogen bulb based) for the visible and near-IR (0.5 to 2.0 µm). These sources are used for stability testing and include attenuators/aperture plates to allow the radiance to match as close as practical the spectral energy density for the faint and bright target cases from the Ariel mission requirements [1]. In order to verify the payload wavelength calibration, spectral scanning capability is provided by a triple grating monochromator.

2.3 Injection Module and Target projector

The illumination collimator assembly sends a narrow beam (22 mm dia) from the illumination module through the cold shrouds of the CTR. For injection into Ariel the beam is first re-imaged with the injection optics using a parabolic mirror, and then recollimated for sub aperture illumination of Ariel M1 (Figure 6). The Injection Module includes the necessary mirrors and actuators to maintain alignment of the OGSE Illumination module test beam onto the OGSE Target Projector. Fold mirrors allow the Injection Module & Target Projector to meet the accommodation requirements within the Ariel CTR.

The OGSE Target Projector provides direct illumination of a sub-aperture of the Ariel M1 mirror by beam expanding the beam from the Illumination and Injection module to fill a ~300 mm diameter aperture off axis parabolic reflector (Figure 6). Since the OGSE is only partially illuminating M1 and additional powered optic (beam expander) that forms part of the OGSE is required within the Ariel PLM to ensure that the spectrometer and Fine Guidance Sensor (FGS) modules are illuminated with the correct focal ratio (cone angle). The focal ratio change is needed to produce the correct diffraction limited point spread function at the focal planes.

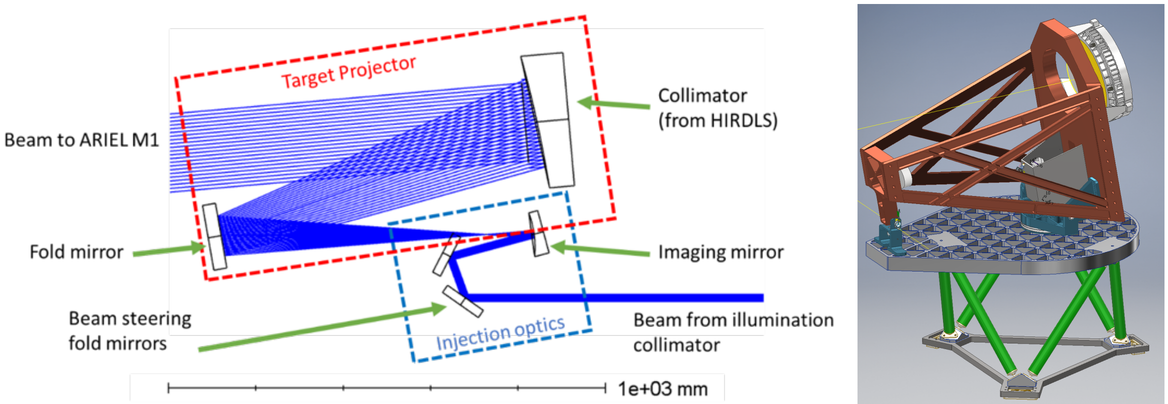

Figure 6. Target Projector and Injection module concept (left), Injection and module and target projector accommodation within the CTR (right). OGSE beam diameter at the entrance to the injection module is currently 22 x 14.6 mm

2.4 Beam expander module

The beam expander module (Figure 7) expands the ~5 mm diameter beam from the partial illumination of the Ariel telescope by the target project to ~20 x 13.3 mm to match the input focal ratio required by the Ariel spectrometers and FGS. The beam expander module is designed to be mounted onto the PLM optical bench between the M4 and M5 mirrors. It includes two powered optical elements (Off-axis parabolic reflectors) and a periscope mirror arrangement to return the beam to the common optics optical-axis. The Beam Expander is contained in single enclosure containing an optical bench and is designed to be a plug-in module that is removed once ground testing is completed.

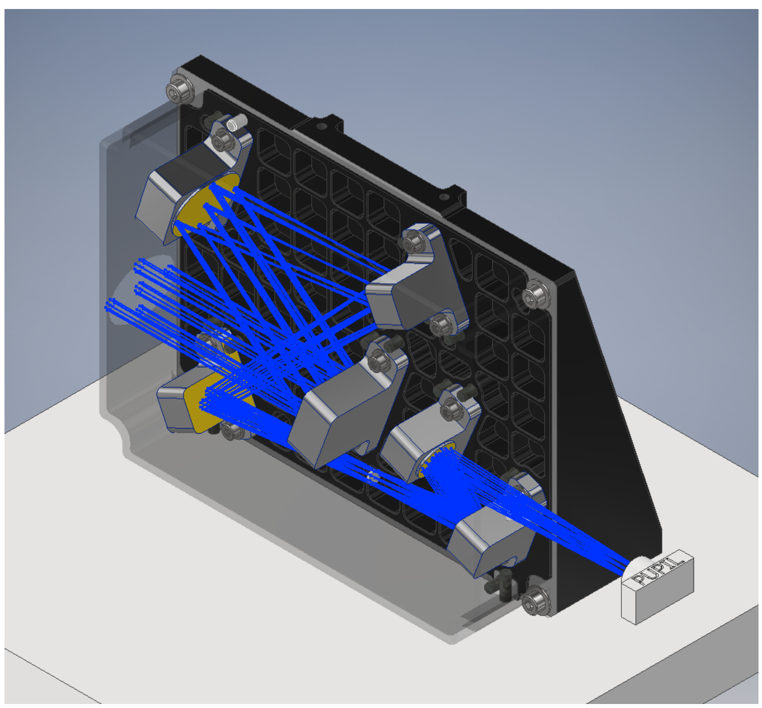

Figure 7. OGSE Beam expander module enclosure and optical layout.

3. ARIEL OGSE END TO END OPTICAL DESIGN

The OGSE consists of multiple elements that act together to deliver the test beam to the common optics. Careful consideration of the fields and apertures through all elements must be considered to ensure that the test beam is not vigneted and accurately replicates the in-flight beam emerging from the telescope exit pupil towards the common optics.

Whilst the complete optical system includes the optics that relays the sources (Figure 5, Figure 6), the imaging portion of the system only begins at the beam output from the integrating sphere in the illumination module. An unfolded schematic of the OGSE optical design from this point is given below with representation of only powered mirrors and the defining apertures.

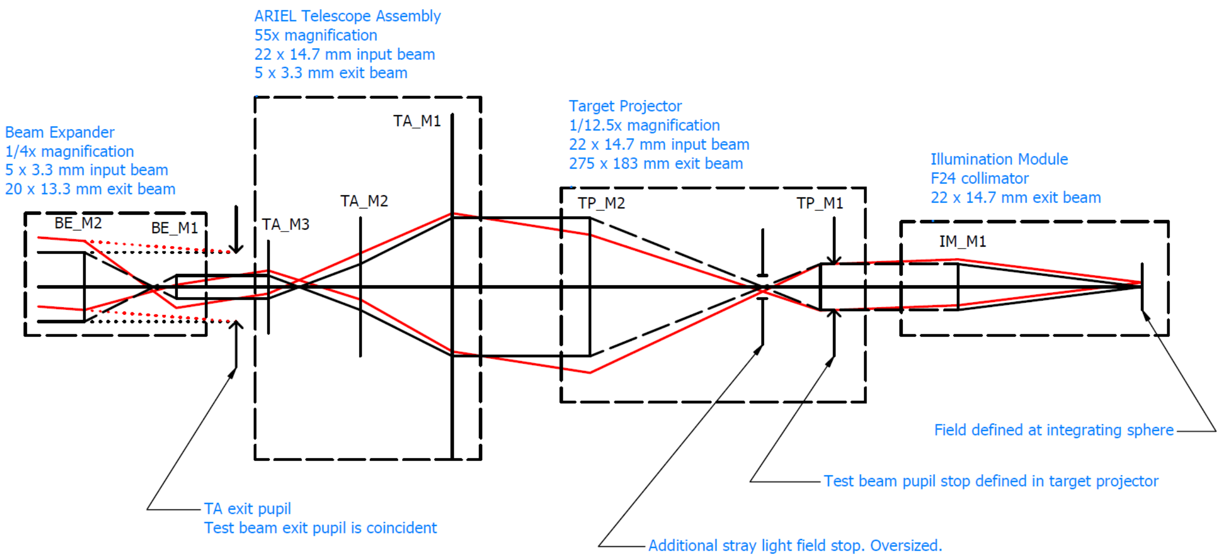

Figure 8. Simplified OGSE end to end optical layout. On axis beam in black, off axis in red. Note, the illumination module F/24 is the geometric average of the major and minor directions.

4. PLANED PAYLOAD LEVEL TESTS.

The OGSE will be used to verify the performance of the Ariel PLM sub-systems including verification of calibration performance derived from the Ariel PLM calibration requirements during subsystem level testing [1,3]. Below selected payload level tests are summarized with a top-level description of how the OGSE will be used to make these measurements.

4.1 Verification of the radiometric calibration

The radiometric calibration allows the Ariel detector signal to be related to the stellar irradiance. This can be derived by injecting a known spectral power from the OGSE and comparing that to the measured signal at the focal plane. This measurement will be performed spectrally with the monochromator and with the point sphere output. The knowledge of the relative radiance of the monochromator with wavelength will be measured by a thermopile which is assumed to have a spectrally flat response.

4.2 QE × throughput maps

For all but the brightest targets (e.g. HD219134), Ariel is designed to be a photon noise-limited instrument, therefore, the QE × throughput sets the noise floor for most targets. Maps of this quantity will be generated in a similar way to the end-to-end radiometric calibration, except here the diffuse sphere output will be used to uniformly illuminate regions of the focal planes. Similar to the radiometric calibration the method relies on comparing the measured signal to a known absolute radiance injected into Ariel. Since the detector QE is degenerate with the optical with the throughput, it is the product that is measurable at payload level.

From these QE×throughput maps, unresponsive and hot pixels can be identified. These bad pixels can then be subtracted from scientific observations.

4.3 Radius of encircled energy/ spectral resolutions verification.

The spectral resolution of the payload is limited by the radius of encircled energy. To verify the radius of encircled energy of the payload after cooldown, the OGSE will illuminate the payload with a monochromatic point source and the size of the image on the focal plane can be verified. However, gravity causes a sag of the primary mirror, this, along with the sub-aperture illumination of the payload, means this is just a qualitative check of the optical performance.

4.4 Flat field/ jitter susceptibility

Even with its envisioned stability, Ariel is affected by pointing jitter, introducing photometric variability and effectively an additional noise term. This needs to be suppressed. This photometric variability arises when the image of the star moves on the focal plane, and the responsivity of the detector has a spatial dependence. As such, the flatfield response of the focal plane array needs to be known with high accuracy (<0.5%).

To produce the flat field, the OGSE will use the broadband sources and raster scan the point source across the focal plane. After correcting for source variability, changes in detector signal can be attributed to pixel responsivity. This can be inverted to produce a local flatfield.

4.5 Gain drift verification

A component of the payload noise budget is any variation of gain with time. In this context, the gain is defined as any quantity that multiples the signal in the end-to-end optical and electronic chain. Gain drifts, therefore, include changes in throughput, QE, charge to voltage conversion etc. Since a change in gain is degenerate with a change in source flux, to verify the payload is stable to 40ppm sqrt(hr), OGSE source variations must be stable to this level. It is planned this level of OGSE source stability will be achieved by monitoring and correction using broadband reference detectors mounted on the integrating sphere.

4.6 Additive drifts/ Read noise/ persistence/ random telegraph signal

Additive drifts, read noise, persistence & random telegraph signal also contribute to the payload noise budget and therefore their impact needs to be verified. In this context, additive drifts are defined as any variability that adds to the signal e.g. dark current drifts/ thermal emission drifts etc. All of these effects are verified by observing the detector time series data with the OGSE sources shuttered.

Read noise can be distinguished from additive drifts by increasing the readout rate of the detectors. Persistence is measured after a long (~10hr) illumination period with the OGSE sources. Random telegraph signal can be seen by looking for bi-stable variability.

4.7 Dark current

The dark current can be measured from the increasing signal during long (>hours) integrations with the sources shuttered.

4.8 Temperature dependence/ thermal balance testing

Temperature is known to affect various calibration products e.g. the dark current. To assess the sensitivity of the derived calibration products to changes in temperature, the temperature of the base of the payload can be varied over the range of operational temperatures 215-293K. Of particular note, are the potential temperature dependence of the (1) the pointing (2) the point spread function, (3) the detector gain and (4) the dark current. The temperature dependence of these parameters will be measured using the methods described in their corresponding sections.

In addition to verifying the temperature dependence of calibration products, temperature sensors will be used to verify the cryogenic performance of the payload at each warm boundary condition temperature.

4.9 Wavelength calibration & relative pointing offset between Ariel channels

The wavelength calibration and channel co-alignment are both assed by centroiding spots on the focal plane. To produce a spot, the monochromator and point sphere output are used. Initially, the co-alignment and wavelength calibrations are assessed by spectrally scanning an on-axis source. However, since the Ariel spectrometers are essentially slitless, the wavelength calibration will be pointing dependent. Therefore, the wavelength calibration and co-alignment will be re-assessed for off-axis rays.

4.10 Non-linearity & saturation

Ariel uses MCT detectors which are known to exhibit a non-linear behaviour with flux under some conditions. Specifically, the responsivity depends on the accumulated signal since the last detector rest. To verify the non-linearity correction derived at subsystem level, the OGSE will use the extended source and the monochromator to produce uniform illumination of a focal plane. The focal plane integration time will then be varied such that the measured signal vs integration time can be plotted. Deviations from linear can be used to generate a linearity correction.

4.11 Crosstalk & gain

The crosstalk and gain can both be assessed using the mean-variance method. The OGSE source will be attenuated such that the detectors are photon noise limited. When this is the case, the variance of the signal provides the number of detected electrons. This can be compared to the measured signal in digital units to get the gain in ADU/e.

Moreover, we also have prior knowledge that photon noise should be spatially uncorrelated across the detector array. However, if there is capacitive coupling between the pixels, the coupling spatially smooths photon noise, leading to a spatial correlation in the photon noise. Therefore, by looking for spatial correlations in the photon noise crosstalk maps can be generated.

5. CURRENT STATUS

The Ariel OGSE has been through a preliminary design review, with a critical design review in late 2022. The first tests of the OGSE are scheduled for summer 2023 when the Target Projector will be integrated with the CTR for a vacuum cryo "blank test" to confirm thermal performance. The Ariel flight unit PLM test campaign is scheduled for early 2026.

6. CONCLUSIONS

The Ariel Optical Ground Support Equipment has been designed to allow testing of the complete end-to-end performance of the integrated payload module during thermal vacuum testing. The Ariel OGSE has been designed for cryogenic operation and to meet the demanding requirements of the Ariel mission for photometric stability and photon noise limited performance.

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