

New facility for straylight verification applied to the ARRAKIHS mission

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ABSTRACT

In the framework of the ARRAKIHS mission, the second F-class mission of the European Space Agency, a dedicated facility for straylight verification has been developed at the Centre Spatial de Liège. The facility is designed to easily characterize the straylight performance of optical instruments and subsystems.

It combines several key elements: a large high-performance black tent providing a low-scattering environment, a broadband collimator covering wavelengths from the visible to the near-infrared, a fully mechanized test bench enabling precise alignment and scanning capabilities, and a detector assembly operated within an ISO 5/7 clean environment.

This configuration enables the characterization of both in-field and out-of-field straylight contributions and provides flexible adaptation to a variety of instrument geometries and test configurations, such as optical baffles alone or imaging instruments.

This paper presents the design and implementation of the facility, together with an analysis of its optical performance. The facility is first applied to the straylight verification of the ARRAKIHS baffle assembly, providing an initial assessment of its measurement capabilities and achievable straylight sensitivity.

Keywords: Straylight, Facility, Calibration, ARRAKIHS

1. INTRODUCTION

Straylight has become a critical performance driver for modern space-based optical instruments. As detector sensitivities increase and scientific requirements tighten, straylight from internal reflections, scattering surfaces, or external sources can significantly degrade image contrast and bias photometric measurements. To mitigate these effects, dedicated straylight control strategies (optimized baffle geometries, low-reflectance coatings) are systematically implemented during instrument development.

The Centre Spatial de Liège (CSL) has a long-standing heritage in this domain, having designed, manufactured, and qualified several straylight baffle assemblies for space missions¹⁻⁴. While numerical straylight modeling using ray-tracing software has become increasingly sophisticated, experimental verification remains essential. Measurements are required both to validate model assumptions and to quantify straylight contributions that are difficult to simulate, such as scattering from complex surfaces, coating defects, or assembly tolerances.

However, straylight testing is inherently challenging. It requires large, low-scattering environments, stable illumination, precise alignment capabilities, and sensitive detection systems. Historically, CSL developed custom straylight test setups tailored to the needs of individual missions. Although effective, these project-specific infrastructures involved significant development effort and offered limited reusability. As the number of missions requiring straylight verification increases, the need for a flexible, modular, and permanent facility has become evident.

In the context of the ARRAKIHS mission (the second F-class mission of the European Space Agency), CSL initiated the development of a new straylight verification facility. ARRAKIHS aims to perform ultra-low-surface-brightness imaging of faint stellar structures in the outskirts of nearby galaxies. This scientific objective imposes stringent straylight requirements on the instrument, particularly for the suppression of off-axis illumination and the minimization of internal

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scattering. The mission therefore provided an ideal framework for designing and commissioning a versatile facility capable of supporting both subsystem- and instrument-level straylight characterization.

The resulting facility combines several key elements:

- a large high-performance black tent providing a controlled low-scattering environment,
- a broadband collimator covering wavelengths from the visible (VIS) to the near-infrared (NIR),
- an MGSE enabling precise alignment and scanning,
- and a detector assembly operated within an ISO 5/7 clean environment to ensure measurement stability and contamination control.

Beyond ARRAKIHS, the facility was conceived as a long-term infrastructure intended to serve a broad range of applications. Its large working volume, modular mechanical interfaces, and wide spectral coverage make it suitable for straylight testing of optical baffles, telescopes, imaging instruments, and ground-based prototypes. The ability to measure both in-field and out-of-field straylight contributions further enhances its versatility.

This paper presents the design, implementation, and performance of the new straylight verification facility. Section 2 introduces the ARRAKIHS mission and its straylight requirements. Section 3 describes the facility architecture, including the black tent, collimator, MGSE, and detector assembly. Section 4 provides an assessment of the facility performance based on the straylight verification campaign of the ARRAKIHS baffle assembly. Section 5 concludes with perspectives on future applications and planned upgrades.

2. TESTING THE STRAYLIGHT ASSEMBLY OF THE ARRAKIHS SPACE MISSION

The ARRAKIHS space mission

ARRAKIHS is part of ESA's fast mission in its Science Program, meaning a development time of less than 10 years and based on reused, flight-proven technologies. The purpose of the “Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys” (ARRAKIHS) mission is to unveil the Λ -Cold Dark Matter (Λ CDM) of the universe by exploring ultra-low surface brightness⁵.

The scientific objectives focus on detecting faint satellite galaxies gravitationally bound to their host galaxy, as well as stellar streams produced by the tidal disruption of accreted satellites. To achieve this, ARRAKIHS will operate two binocular telescopes from Satlantis company, integrated Standard Imager for Microsatellites (iSIMs) providing wide-field imaging at extremely low surface brightness levels.

The mission will image approximately 50 square degrees of sky per year, reaching unprecedented sensitivity:

- 31 mag/arcsec² at 0.8 arcsec resolution in two visible bands (VIS1: 280.4–420.0 nm, VIS2: 380.8–863.4 nm),
- 30 mag/arcsec² at 1.25 arcsec resolution in two near-infrared bands (NIR1: 857.2–1255.0 nm, NIR2: 1167.6–1567.0 nm).

These measurements will complement JWST and Euclid observations by providing wide-field, ultra-deep imaging of galactic halos, enabling a more complete understanding of galaxy assembly histories.

Figure 2-1 shows the instrument space segment preliminary design.

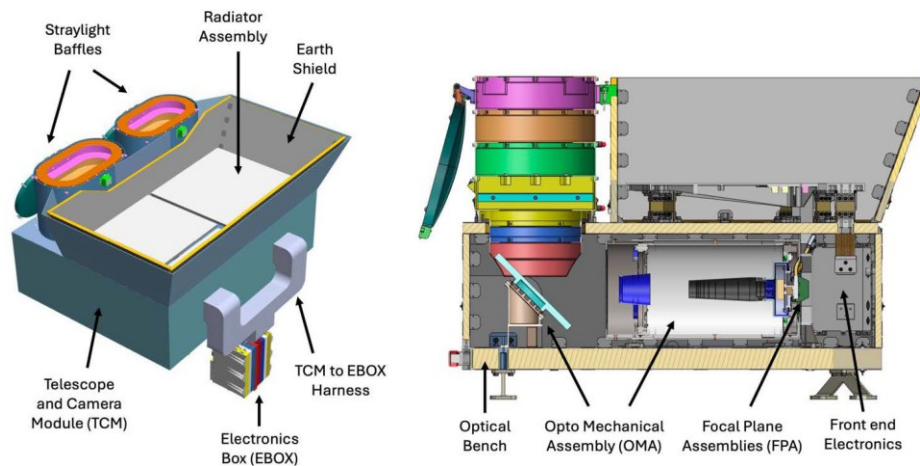


Figure 2-1: The ARRAKIHS instrument space segment preliminary design. Left: the full instrument, showing both the telescope and the camera module, on top of the satellite platform. Right: A cut, showing the VIS binocular and fold mirror.

Straylight baffle assembly (SBA)

As the ARRAKIHS payload module will observe ultra-low surface brightness, straylight control is a key parameter for the success of the mission. CSL is responsible for the straylight analysis and its mitigation for the payload module.

The Straylight Baffle Assembly (SBA) developed at CSL consists of two baffles, one for each binocular telescope, combined with a protective cover used during launch. Each baffle is mounted at 90° relative to its corresponding iSIM and includes folding mirrors that redirect the beam toward the instrument, as depicted in Figure 2-1. The design is built upon CSL heritage from missions such as CHEOPS and CoRoT, with adaptations to meet ARRAKIHS's more stringent straylight requirements^{3,6,7}. The cover mechanism is derived from the CHEOPS design, with updated kinematics and materials. A detailed description of the SBA architecture is part of a dedicated paper⁸.

The baffle interior includes a combination of common vanes (shared by both telescopes) and dedicated vanes optimized for each iSIM. Figure 2-2 shows the vanes from the fold mirror point of view. These vanes are designed to suppress off-axis illumination and reduce multiple scattering paths. All the vanes are black-anodized or black-coated. The trade-off is part of the breadboarding activity described in the next section.

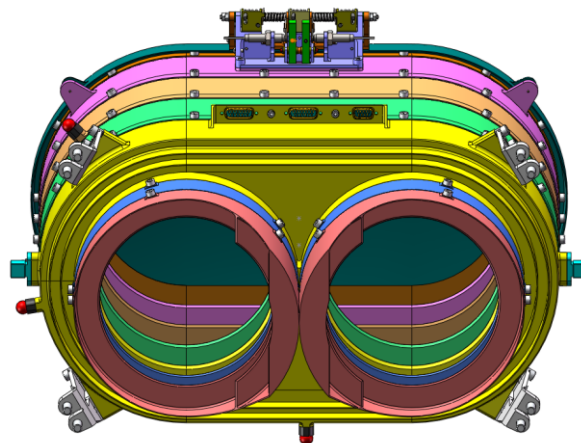


Figure 2-2: SBA, from the fold mirror point of view.

Breadboard development and derisking

During Phase B, two SBA breadboards were manufactured to derisk the development schedule⁹.

- The first breadboard underwent thermo-mechanical qualification (vibration and thermal-vacuum testing) and includes a functional cover mechanism for deployment tests.
- The second breadboard is dedicated to straylight measurements. It is mechanically identical but fully black anodized and has no cover.

Since both breadboards will evolve into Structural and Thermal Models (STMs), it was decided to apply a black paint coating to the mechanical breadboard as well. This enables a direct comparison between black anodization (from Steiger) and black paint coating (Aeroglaze Z307) in terms of straylight performance, an important trade-off for the final flight model.

Straylight test objectives and methodology

A straylight verification campaign is planned to ensure that the SBA meets the Normalized Detector Irradiance (NDI) performance requirements and tolerances. Because the baffle geometry is not rotationally symmetric, measurements must be performed along both the short and long axes.

The test requires a fully dark environment to minimize background scattering. For this purpose, the SBA is installed inside the black tent described in Section 3. The baffle is illuminated with a monitored, collimated beam, and the amount of light exiting the baffle is measured and compared with predictions from the straylight ray-tracing model.

The usable diameter of the collimated beam is 90 mm, smaller than the baffle aperture. To cover the full entrance pupil, a scanning procedure is implemented using a dedicated MGSE. The detector records the signal as a function of the baffle orientation and beam position, enabling reconstruction of the NDI curve. A normalization measurement is performed by directly illuminating the detector without the baffle in place.

This test campaign provides the first quantitative assessment of the SBA straylight performance and serves as a validation case for the new facility. The results are described in a dedicated paper in this conference¹⁰.

3. FACILITY DESCRIPTION

The straylight verification facility is installed inside an ISO 5 / ISO 7 cleanroom at the CSL. It consists of a large black tent providing a controlled low-scattering environment, a fiber-fed broadband collimator, and a Mechanical Ground Support Equipment (MGSE) enabling precise alignment and scanning. Both the collimator and the MGSE can be reconfigured depending on the instrument under test, making the facility adaptable to a wide range of straylight verification campaigns.

The illumination source is located outside the tent and fiber-coupled to the collimator. A dedicated monitoring assembly continuously tracks the source stability.

Black tent

The black tent is designed to isolate the test setup from ambient straylight originating from the cleanroom environment. It measures 6000 × 1950 × 2050 mm (excluding wheels). Figure 3-1 shows a 3D view of the tent exterior.

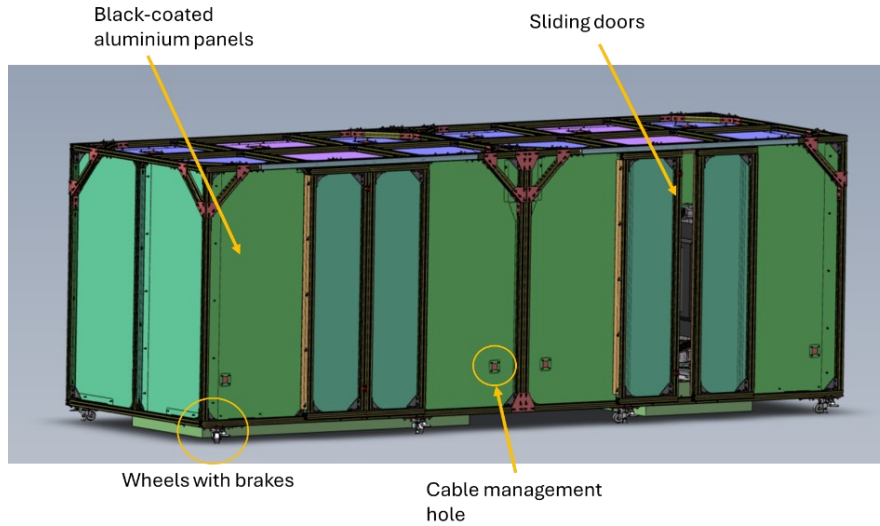


Figure 3-1: 3D view of the black tent OGSE

The structure is composed of multiple aluminum panels coated with a mat, heat-resistant black paint (Europolveri polyester). This coating was selected for its low reflectance and robustness under repeated handling. Figure 3-2 presents the hemispherical reflectance of the paint, measured at CSL using a PerkinElmer spectrophotometer.

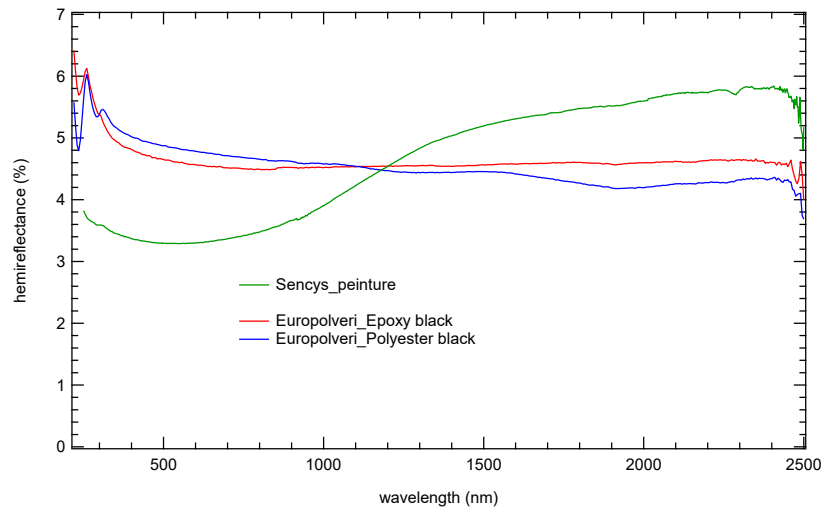


Figure 3-2: Hemireflectance of black paints.

To minimize floor reflections, the interior ground surface is covered with BK5 black cover sheets (rubbered face, Thorlabs). The junction between the floor and the walls is treated using BKF12 skirts (Thorlabs), and all screws or discontinuities are masked with T743 black tape. Reflectance measurements provided by Thorlabs indicate that BK5 exhibits a nearly flat response around 4% across the 200–2500 nm spectral range, while BK12 shows slightly higher reflectance in the NIR ($\approx 7\%$) compared to the VIS ($\approx 4\%$)^{11,12}.

Figure 3-3 illustrates the interior of the tent, highlighting all black materials. Additional baffling elements are installed around the collimator to suppress residual scattering; these components are coated with standard commercial heat-resistant black paint (Sencys).

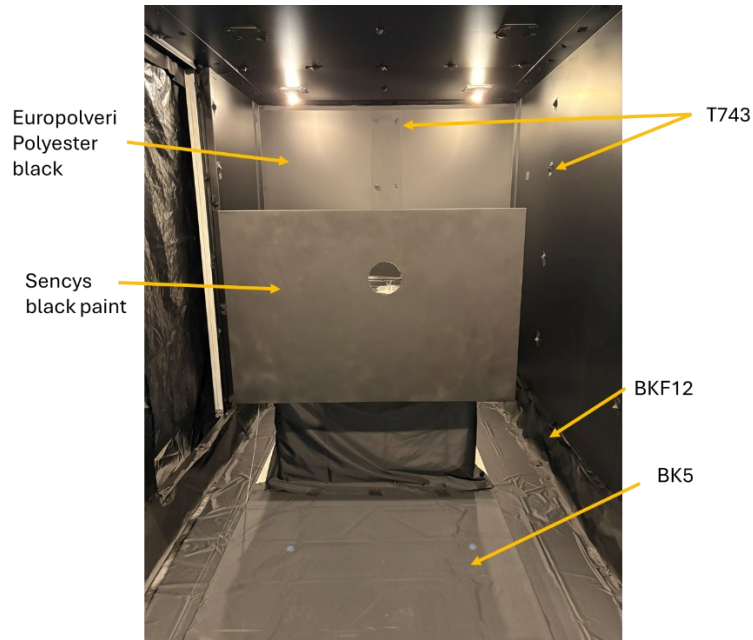


Figure 3-3: Black materials inside the tent

Cable management is ensured through dedicated apertures integrated into the tent panels (visible in Figure 3-1). These apertures allow routing of power, control, and data cables without compromising the straylight isolation.

Access to the tent is provided by two sliding doors, enabling straightforward integration of the test materials onto the MGSE. The entire tent is mounted on lockable wheels, allowing it to be repositioned within the cleanroom as needed. Figure 3-4 shows the door in open and closed configurations.



Figure 3-4: View of door (from inside) – open and close

For integration work, up to twelve standard E27 LED bulbs (6.5 W) can be installed inside the tent. Eight bulbs are currently used. All illumination is switched off during straylight measurements. Figure 3-5 shows the OGSE collimator and the LED bulbs.

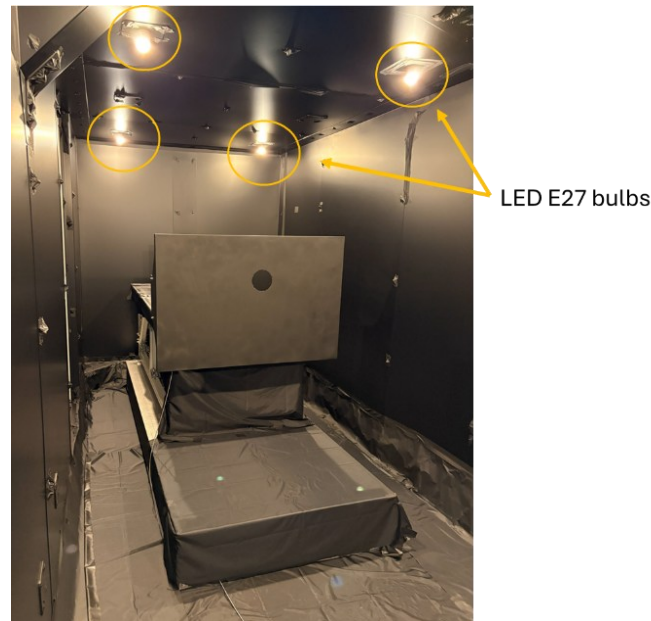


Figure 3-5: Collimator OGSE and E27 LED bulbs highlighted

Source & monitoring assemblies

The facility is equipped with several fiber-coupled laser sources covering wavelengths from the far-UV to the NIR. The source assembly is modular and can be reconfigured to meet the spectral range, power level, and stability requirements of a given straylight test. For the ARRAKIHS straylight test campaign, an initial measurement was performed using the Akela TRIO-3LD17 808 nm laser, and a second measurement is planned with the 320 nm UV source.

The architecture includes a fiber-coupled diode laser, a first fiber-coupled collimator, an attenuation stage composed of motorized filter wheels with neutral-density filters, a second fiber-coupled collimator injecting the beam into the FPA fiber optics, and a monitoring stage using one or two photodiodes depending on the expected dynamic range.

This configuration ensures stable illumination, controlled attenuation, and continuous monitoring of the injected flux.

The source assembly can be updated with any required wavelengths. Currently, CSL is able to provide measurements at 320 nm, 450 nm, 650 nm, 670 nm, 750 nm, 808 nm and 1375 nm.

Collimator

To illuminate the instrument under test, a dedicated collimator OGSE was developed. It consists of an optical table, a supporting frame with an isostatic, repeatable mechanical interface, a breadboard, an off-axis parabola (OAP) and its mount, a focal plane assembly (FPA), and a set of internal baffles.

The supporting frame is clamped to the optical table and includes a kinematic interface allowing the collimator breadboard to be removed and reinstalled without loss of alignment. This feature is essential for switching between different OGSE configurations, if needed, while maintaining repeatability.

The FPA includes a pyramid mount, a pupil stop, an adjustment mechanism, and laser-tracker nests for alignment. The pyramid mount holds the $400 \times 400 \mu\text{m}$ multimode square-core fiber ferrule, whose output is positioned at the optimal focus of the OAP.

The current pupil stop is a 10-mm-diameter aperture located 160 mm from the fiber end. It limits the collimated beam to 90 mm, but it can be replaced with a different one depending on the required beam diameter. A tubular baffle, coated with Strayprotect, suppresses straylight around the pupil stop.

The OAP has a useful diameter of 230 mm, a parent focal length of 1500 mm, and an off-axis distance of 150 mm. It is manufactured from LK7 and coated with aluminum. The measured surface figure error is 58 nm PtV, ensuring high-quality collimation over the full beam diameter.

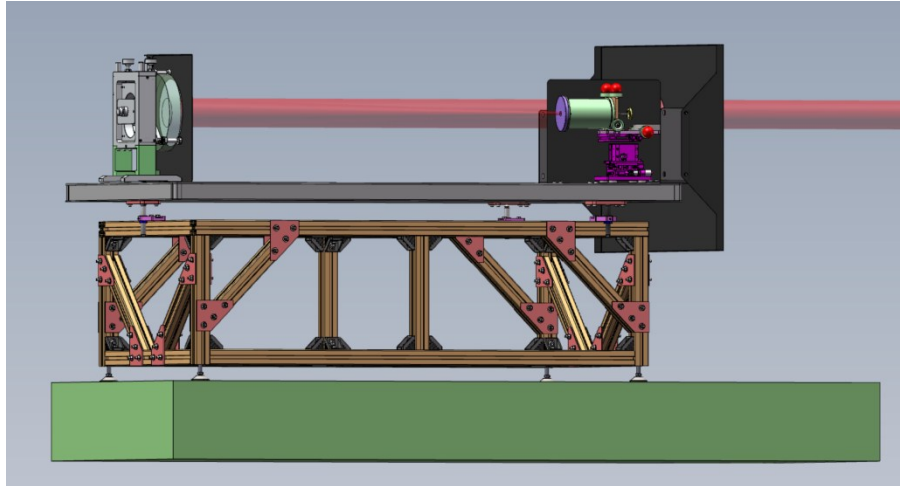


Figure 3-6 : Supporting frame, the OAP and the FPA view.

MGSE

A dedicated MGSE is installed inside the dark tent to support and position the instrument under test. Its primary functions are to provide a mechanical interface with the instrument, in this case the Straylight Baffle Assembly (SBA), and to accurately set the instrument line-of-sight (LOS) in azimuth, elevation, and lateral decentering relative to the collimator beam.

For the ARRAKIHS straylight verification campaign, two MGSE configurations are foreseen: a vertical configuration and a horizontal configuration. Each configuration requires a specific mechanical interface for the SBA, and switching between them involves disassembling and realigning the interface. All illustrations in this paper correspond to the vertical configuration.

The current MGSE architecture includes an optical table, a rotation stage equipped with an absolute encoder, two perpendicular translation stages with 600 mm travel, the SBA mechanical interface, and the detector assembly (described in the next section).

This setup enables precise positioning of the baffle relative to the collimated beam and supports the scanning strategy required to cover the full entrance pupil. The entire MGSE is aligned using a laser tracker to ensure repeatability and geometric accuracy.

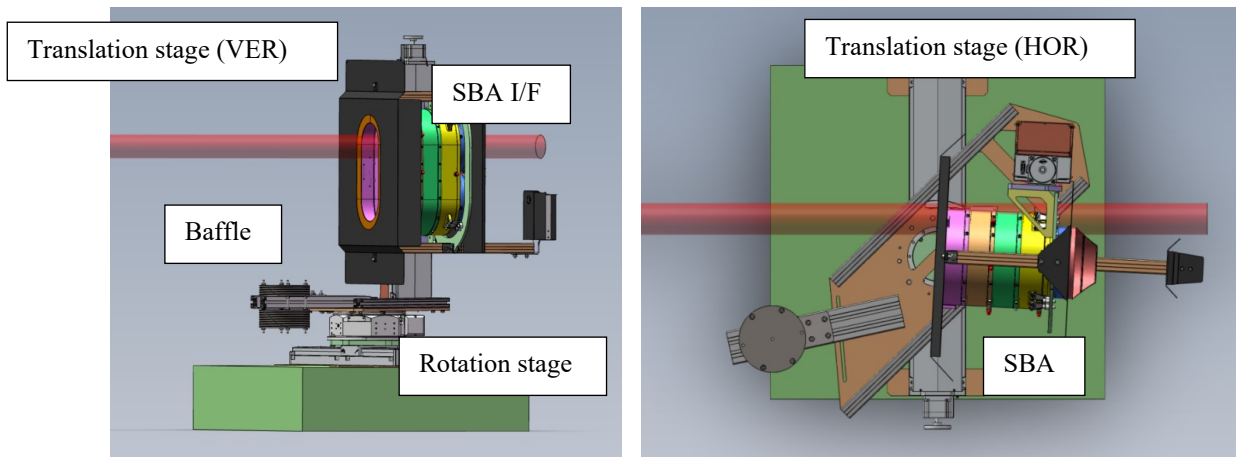


Figure 3-7 : MGSE with the SBA in vertical configuration. Left: side view. Right: top view.

The MGSE can be upgraded depending on the project. In late 2026, it will be modified to accommodate the front baffle assembly of the Vigil Heliospheric Imager². In early 2027, the ARRAKIS iSIM telescopes, see Figure 2-1, will be tested in the facility. Since there is no need for large translations and extensive scanning, the two translation stages will be replaced with a hexapod, providing six degrees of freedom of positioning. The rotation stage will remain in place.

This upgraded configuration will become the default MGSE setup for the facility. It offers high adaptability to different instruments and test geometries, while maintaining the precision required for straylight characterization.

Detector stage

Since no instrument is placed downstream of the SBA during the straylight test, a dedicated camera is installed directly behind the baffle on the MGSE. The detector used for the ARRAKIS breadboard campaign is a ZWO ASI6200 Pro, a low-noise scientific CMOS camera equipped with a large, cooled sensor. An objective lens is mounted on the camera to image the origin and spatial distribution of straylight inside the SBA. CSL is also equipped with a ZWO ASI990 Pro for infrared capabilities, up to 1750 nm.

For straylight measurements performed on complete instruments or telescopes, it is generally preferable to use the instrument's own focal plane detector, ensuring that straylight is measured under representative optical conditions. This approach will be adopted during the ARRAKIS iSIM test campaign planned for early 2027.

CSL is also investigating the use of a lock-in camera (Heliotis Helicam 4C.2-S40U) to further improve straylight rejection within the facility. Lock-in detection would allow synchronous demodulation of the signal and significant suppression of background noise. The monitoring stage already includes the required optical chopper, making the facility compatible with future lock-in measurements.

Software controlled

To automate the measurement process and ensure repeatability, dedicated control software was developed in MATLAB. The software manages all hardware elements involved in the straylight test, including the laser-diode controller, the picoammeter used for monitoring photodiode readout, the motorized filter wheel for attenuation control, the two translation stages, the rotation stage, and the detector.

This centralized control architecture enables fully scripted measurement sequences and ensures consistent test conditions across repeated scans of the entrance pupil.

The software was designed to be modular, allowing straightforward updates when the MGSE or detector stage evolves. Future upgrades, such as the integration of the hexapod or the lock-in camera, can be incorporated with minimal changes to the control logic, ensuring long-term maintainability of the facility.

4. FACILITY PERFORMANCE

Calibration of the test camera

The ASI ZWO 6200MM Pro camera used for the straylight measurements was calibrated in absolute radiometric units to convert the recorded DN/s into optical power (W) at the detector plane. The calibration was performed at 808 nm using a transfer method based on a calibrated spectroradiometer (SR4500A) equipped with a certified 1° lens accessory.

Figure 4-1 shows the calibration setup inside the black tent. The collimator OGSE was used together with a diffuser placed in transmission in the collimated beam. Using the MGSE, the camera and the SR4500A were sequentially positioned at the same location in the beam, ensuring that both instruments measured the same optical flux.

Five measurements were performed at different camera gain settings. All signals were corrected for dark current. After compensating for the gain (i.e., normalizing to an equivalent gain of zero), the resulting conversion factor between DN/s and optical power is: $2.5532 \times 10^{-18} \text{ W/ (DN/s)}$.

This value represents the absolute responsivity of the camera at 808 nm for the optical configuration used during the straylight test.

A comparison was performed with the responsivity derived from the manufacturer's datasheet. The difference between the measured and datasheet-based values is 27.5%, which is considered reasonable given uncertainties and incomplete information in the datasheet, unit-to-unit variations between cameras, and the fact that the transmission of the 12 mm C-mount VIS–NIR fixed focal length lens is not provided by the manufacturer and therefore not included in the datasheet-based estimate.

This calibration ensures that straylight measurements performed with the ASI6200 camera can be quantitatively compared to model predictions and to future measurements.

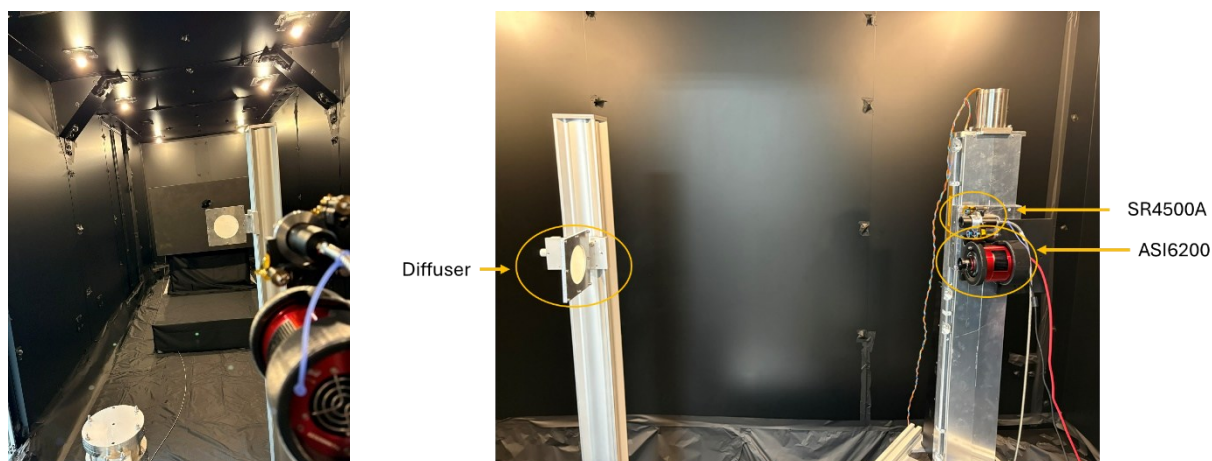


Figure 4-1: Test setup inside the black tent (ASI6200 & SR4500A)

Tent light leakage test

The straylight inside the tent can be intrinsic (scattering within the tent) or extrinsic (light coming from outside). Both were measured. For exterior lighting emanating from the clean room, a visual approach was first performed. This allowed us to pinpoint weaknesses and reduce them (e.g., black taping of the interface between black paints).

Then, a more formal approach was performed. It allows measuring the opacity of the black tent. The ASI ZWO6200MM Pro is calibrated at 808 nm, while extrinsic straylight covers the full bandwidth of the camera. It was measured at several rotational positions of the MGSE. Figure 4-2 shows the mean residual flux over the detector (ON – OFF), indicating very low light leakage from outside to inside. This residual indicates that the black tent straylight rejection is around 10^{-10} , based on an absolute irradiance measurement of the collimator OGSE.

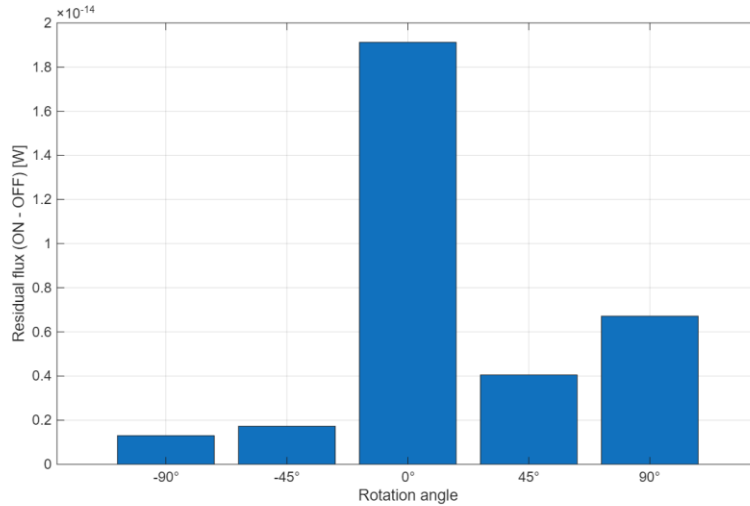


Figure 4-2: Estimation of the residual flux (ON - OFF) due to exterior lights.

Let's note that, with absolute calibration, the acquired signal is compared to an equivalent signal at 808 nm. Classical LED emission in the cleanroom peaks at around 450 nm and 650 nm. The camera response is higher than at 808 nm (two to three times the value). This means that a small signal at those wavelengths can degrade measurements performed at 808 nm.

Scattering within the tent

The second verification is for the scattering within the tent. The overall diffusion of the tent is measured by switching on the collimator. The collimated beam is targeting the black panel of the tent behind the MGSE. Three back panels are compared: the classical black painted one from the tent, as described in Section 3, a white paper sheet, and a Musou black fabric, a very effective black material nearly equivalent to Vantablack¹³.

The straylight contribution of the back-panel configurations was evaluated using the white sheet as a reference. The collimator output was excluded from all configurations using a circular mask of 125-pixel radius, ensuring that the same useful area was considered in each case.

To better isolate the straylight contribution, a common pixel-level threshold of W/pixel was derived from the white-sheet measurement. The common threshold, 2.21×10^{-17} W is defined as the mean plus 0.05 standard deviation. This same physical threshold was applied to the three configurations. The pixels exceeding the common threshold decreased from 36.7% for the white sheet to 4.7% for the black-painted panels and only 0.03% for the Musou Black configuration. Integrating only the signal above the common threshold gives excess straylight powers of 3.09×10^{-12} W, 8.03×10^{-14} W, and 1.78×10^{-15} W, respectively. Relative to the white-sheet reference, this corresponds to a reduction of the straylight excess to 2.6% with the black-painted panels and to only 0.06% with the Musou Black treatment, i.e., reductions of approximately 1.6 and 3.2 orders of magnitude, respectively.

These results are shown in Figure 4-3, with the exceeding pixels colored in red. The first image represents the setup with the interior lights switched on and is used for comparison. Based on this experience, it was decided to definitively install the Musou Black fabric in this region. An upgrade of several panels with Musou Black is planned.

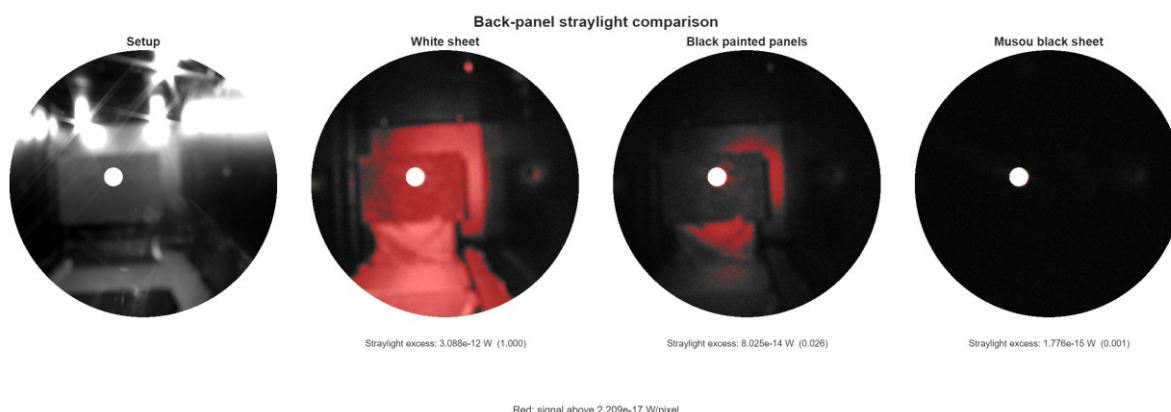


Figure 4-3: Back-panel straylight comparison.

Air diffusion by the collimated beam

Air diffusion is an unavoidable phenomenon and is more important at short wavelengths. Within the tent, when the collimated beam is on, it leads to straylight background noise.

To assess the impact of volume scattering on the black tent background, simulations were performed in FRED, as depicted in Figure 4-4, using a collimated circular source (10 mm radius) and two detectors located at 1 m from the source: one positioned within the direct beam and one outside the beam to isolate the scattered contribution.

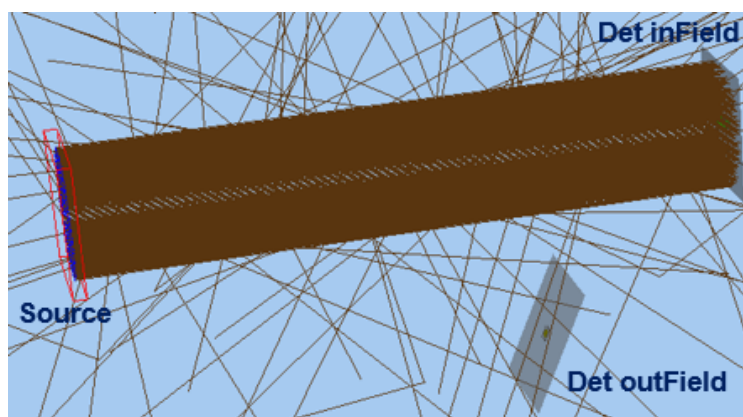


Figure 4-4: Volume scattering simulations in FRED software

The irradiance at the source ($3.18 \times 10^{-3} \text{ W/mm}^2$) was used to normalize the results. Two scattering models were investigated: an isotropic Rayleigh model, parameterized by the scattering coefficient, and a Mie model accounting for the scattering coefficient, particles diameter, and particles refractive index. The scattering coefficient represents the probability of light being deflected by airborne particles per unit propagation distance and depends on both wavelength and air cleanliness. Simulations were carried out at 280, 405, and 808 nm, and the irradiance resulting exclusively from volume scattering was computed at both detectors.

The Normalized Detector Irradiance, defined as the ratio between the scattered irradiance and the source irradiance, was then used to compare the different cases. As expected, volume scattering increases significantly towards shorter wavelengths, while the Mie model predicts a more directional scattering distribution than the isotropic Rayleigh model.

For the Mie model, the NDI measured outside the direct beam increased from 3.14×10^{-8} at 808 nm to 9.42×10^{-8} at 405 nm and 9.42×10^{-7} at 280 nm. The corresponding Rayleigh values were negligible, 3.14×10^{-8} , and 3.14×10^{-7} , respectively. Within the direct beam, the Mie model yielded NDIs of 1.57×10^{-7} , 9.42×10^{-7} , and 2.20×10^{-6} at 808, 405, and 280 nm, respectively.

The achievable straylight rejection in an air-based test is intrinsically wavelength-dependent, as volume scattering establishes a lower bound to the measurable straylight level. The achievable rejection level should therefore be assessed together with the volume-scattering background of the test setup, particularly when characterizing straylight below the 10^{-6} level is required.

5. CONCLUSION

The new straylight verification facility developed at CSL has been successfully designed, implemented, and commissioned in the framework of the ARRAKIHS mission. The combination of a large low-scattering black tent, a broadband collimator, a flexible MGSE architecture, and a dedicated detector stage provides a stable and controlled environment for quantitative straylight measurements. The characterization of the tent opacity, internal scattering, and volume-scattering background demonstrates that the facility achieves straylight rejection levels compatible with the requirements of modern space instruments, with measured leakage below 10^{-10} and panel-scattering reductions exceeding three orders of magnitude when using enhanced black materials.

The first application of the facility to the ARRAKIHS Straylight Baffle Assembly demonstrates its measurement capabilities and confirms its suitability for subsystem-level straylight verification. The absolute radiometric calibration of the test camera ensures measurement traceability and enables direct comparison with model predictions. These results provide a solid foundation for upcoming test campaigns, including characterization of the ARRAKIHS SBA, the Vigil heliospheric imager front baffle, and the ARRAKIHS iSIM telescopes.

Planned upgrades, including integrating a hexapod for improved positioning flexibility, installing additional Musou Black panels, and implementing lock-in detection, will further enhance the facility's sensitivity and adaptability. Beyond ARRAKIHS, this permanent infrastructure is intended to support a wide range of straylight verification activities for both space-based and ground-based optical systems, providing a versatile, high-performance environment for future missions.

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