

Optical verification of the straylight baffle of the ARRAKIHS mission

Colin Dandumont^{*a}, Marine Adam^a, Pascal Barzin^a, Lionel Clermont^b, Olivier Closset^a,
Philippe Franssen^a, Pierre Guiton^a, Stefan Kögl^c, Massimo Lucia^d, Emmanuel Mazy^a,
Alexandra Mazzoli^a, Bertrand Mohring^a, Jean-Yves Plessier^a, Thibaut Prod'Homme^d,
Antonio Rodriguez-Senin^e, Santiago Serrano^f, Laurence Soulat^d, Etienne Lallemand^a

^aCentre Spatial de Liège, University of Liège, Avenue du Pré Aily, Liège, Belgium;

^bSTAR Institute, University of Liège, Belgium

^cKoegl Space, Switzerland

^dEuropean Space Agency, Netherlands

^eArs Galactic, Spain

^fSatlantis, Spain

ABSTRACT

The ARRAKIHS mission, the second F-class mission of the European Space Agency, aims to study dark matter and galaxy formation by observing ultra-low-surface-brightness structures around galaxies. The payload consists of four telescopes (iSIM) operating in four spectral bands spanning the visible-to-near-infrared range.

Achieving the required sensitivity requires extremely stringent straylight control. To prevent out-of-field light from reaching the detectors, two large straylight baffle assemblies (SBAs) have been developed to achieve straylight rejection levels down to 10^{-11} . The design is based on a multi-stage baffle architecture, building on the heritage of the CoRoT mission and CHEOPS mission straylight baffles.

Two breadboards were manufactured: one dedicated to mechanical validation and one to optical verification. This paper focuses on the optical breadboard, representative of the flight design. Its straylight performance was characterized using a dedicated facility developed at the Centre Spatial de Liège, enabling the measurement of extremely low signals and the determination of the system Normalized Detector Irradiance (NDI).

The paper presents the baffle design, the experimental test configuration, and the first measurement results. Laboratory measurements will be compared with ray-tracing simulations to validate the straylight model and confirm the expected performance of the baffle design.

Keywords: Straylight, Baffle, Calibration, ARRAKIHS

1. INTRODUCTION

ARRAKIHS is part of ESA's fast mission line within the Science Programme, implying a development time below ten years and relying on reused, flight-proven technologies. The "Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys" (ARRAKIHS) mission aims to probe the Λ -Cold Dark Matter (Λ CDM) framework by exploring ultra-low-surface-brightness structures around nearby galaxies¹.

The scientific objectives focus on detecting faint satellite galaxies gravitationally bound to their host, as well as stellar streams produced by the tidal disruption of accreted satellites. Achieving these goals requires imaging at extremely low surface brightness levels, making straylight control a critical factor for mission success.

The payload consists of two binocular telescopes developed by Satlantis, the integrated Standard Imager for Microsatellites (iSIMs), providing wide-field imaging across four spectral bands. A preliminary view of the instrument is

*colin.dandumont@uliege.be

shown in Figure 1-1: the full payload module on the satellite platform (left), and a cut revealing the VIS binocular and folding mirror (right).

To meet the mission-level requirement on the Normalized Detector Irradiance (NDI), two large straylight baffle assemblies (SBAs) have been designed. Each SBA is mounted at 90° with respect to its corresponding binocular and includes a folding mirror directing the beam toward the instrument, as illustrated in Figure 1-1.

The Centre Spatial de Liège (CSL) is responsible for the development of both baffles and for the straylight analysis of the entire payload. Two breadboards have been manufactured: one for mechanical validation and one for optical verification. Straylight measurements are performed in a newly developed facility. CSL has a long-standing heritage in this domain, having designed, manufactured, and qualified several straylight baffle assemblies for space missions²⁻⁵.

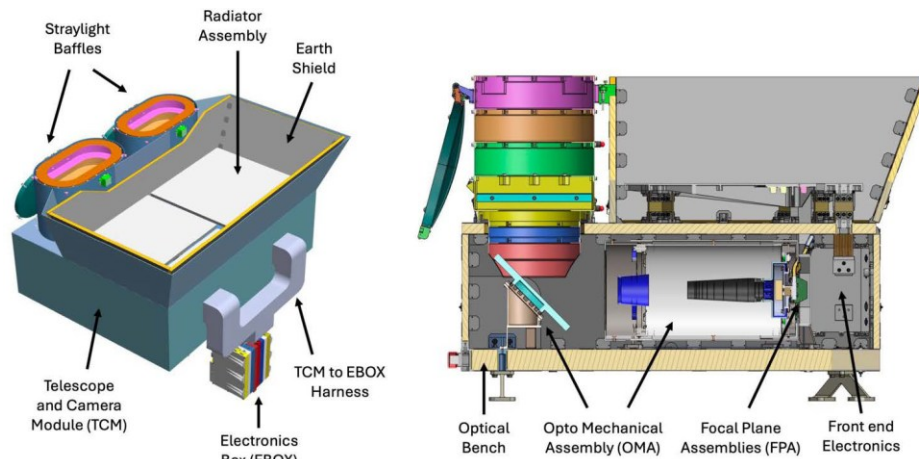


Figure 1-1: The ARRAKIHS instrument space segment preliminary design. Left: the full instrument, showing both the telescope and the camera module, on top of the satellite platform. Right: A cut, showing the VIS binocular and fold mirror.

This paper presents the first straylight measurement results obtained on the ARRAKIHS SBA breadboards, together with preliminary software analysis of the full optical payload. Section 2 describes the SBA breadboards and the test facilities. Section 3 presents the first measurement results for both breadboards. Section 4 details the straylight modeling and software analysis.

2. SBA & TEST FACILITY

Straylight baffle assembly (SBA)

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 1-1. The design is built upon CSL heritage from missions such as CHEOPS and CoRoT, with adaptations to meet ARRAKIHS's more stringent straylight requirements^{4,6,7}. The cover mechanism is derived from the CHEOPS design, with updated kinematics and materials. A detailed description of the SBA architecture is provided in a dedicated paper⁸.

The baffle interior includes a combination of common vanes (shared by both telescopes) and dedicated vanes optimized for each iSIM. Figure 2-1 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 to minimize both specular and diffuse scattering. The trade-off between these surface treatments is part of the breadboarding activity.

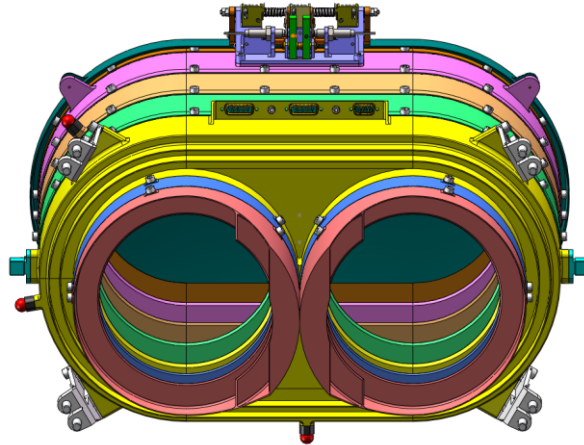


Figure 2-1: SBA, from the fold mirror point of view.

Breadboards manufactured during phase B

To de-risk the development schedule, two SBA breadboards were manufactured during phase B⁹.

- **Breadboard 1 (BB#1)** underwent thermo-mechanical qualification (vibration and thermal-vacuum testing) and includes a functional cover mechanism for deployment tests.
- **Breadboard 1 (BB#2)** is dedicated to straylight measurements. It is mechanically identical but fully black-anodized and has no cover.

Both breadboards will evolve into Structural and Thermal Models (STMs). For consistency, black anodization was also applied to BB#1. However, the process was not performed correctly, resulting in a grayish internal surface. The two anodizations were carried out by different suppliers. Despite this non-conformity, BB#1 was tested in the straylight facility and is compared to the reference black-anodized BB#2 in Section 3.

BB#1 and BB#2 are, respectively, shown in Figure 2-2 & Figure 2-3.

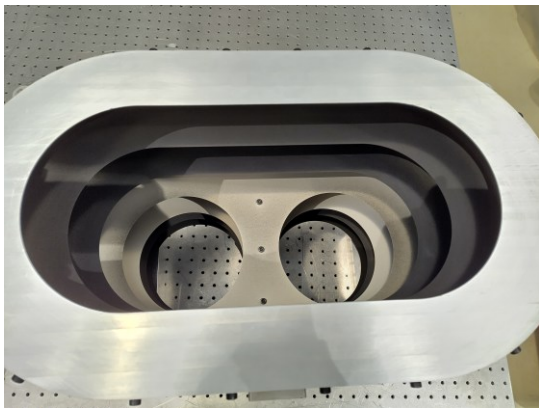


Figure 2-2: BB#1 (uncoated).

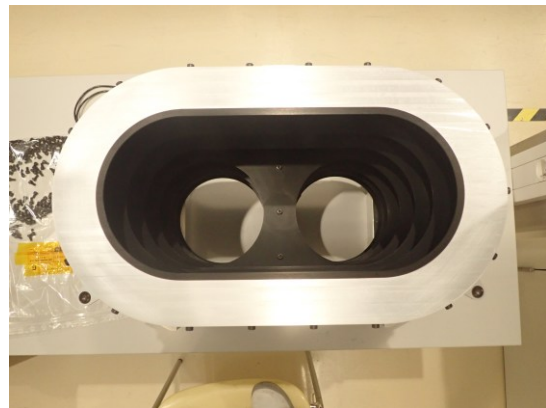


Figure 2-3: BB#2 (black-anodized).

To enable further comparison for the final flight model and improve straylight rejection, BB#1 will be black-painted with Aeroglaze Z307. This coating comparison is part of the breadboarding strategy adopted for the ARRAKIHS mission⁹.

Straylight facility

The SBA straylight performance is assessed numerically using the FRED ray-tracing software, as described in Section 4. However, experimental validation is essential to confirm the predicted rejection levels and to identify potential scattering paths not captured by the model. For this purpose, a new straylight facility was developed at CSL. The design, commissioning, and performance of this facility are detailed in a dedicated paper presented at this conference¹⁰.

The facility is installed in an ISO 5/ISO 7 cleanroom at CSL. It consists of a large black tent providing a controlled low-scattering environment, a fiber-fed broadband collimator covering the VIS–NIR spectral range, and a Mechanical Ground Support Equipment (MGSE) enabling precise alignment and scanning of the SBA. This configuration enables measurement of extremely low irradiance levels and reconstruction of the Normalized Detector Irradiance (NDI) across the full entrance aperture.

Figure 2-4 shows the straylight tent in its horizontal configuration, with the collimator OGSE, the SBA, and the MGSE installed inside the tent.

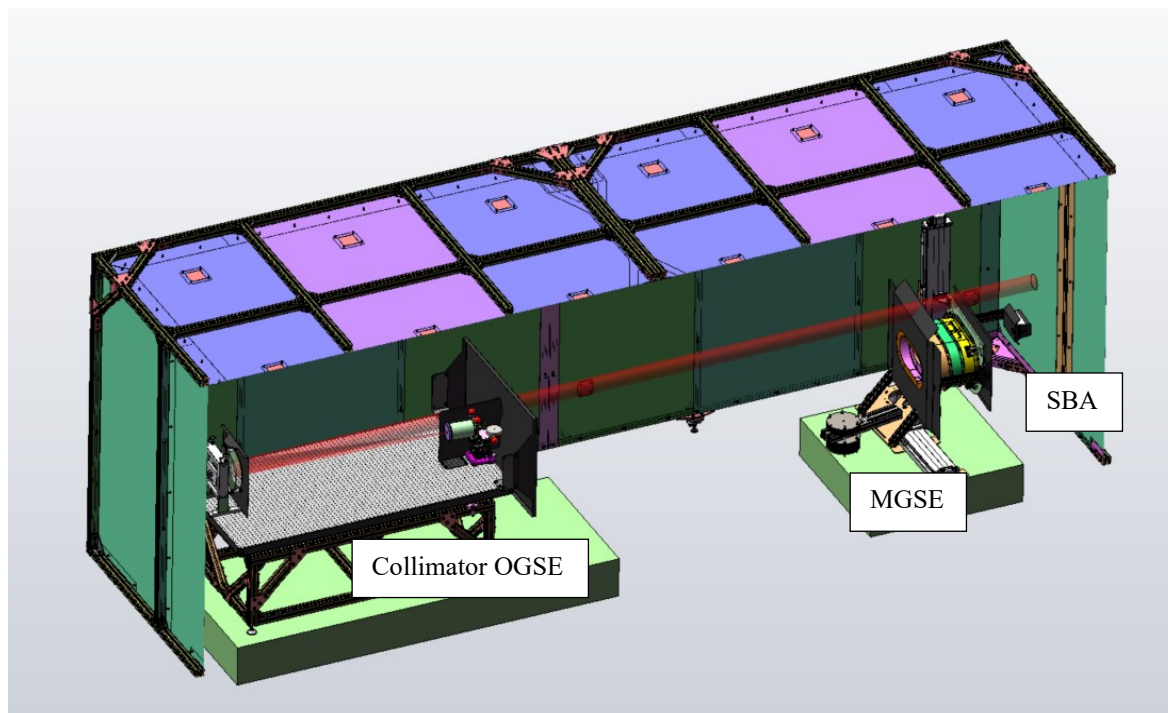


Figure 2-4: Straylight tent with SBA in horizontal configuration.

3. FIRST RESULTS

Straylight test objectives and methodology

The objective of the straylight test campaign is to reconstruct the Normalized Detector Irradiance (NDI) curve of the SBA. Requirements on NDI are represented in Figure 3-1.

The baffle entrance is illuminated by a 90-mm collimated beam. Since the beam diameter is smaller than the baffle aperture, a scanning procedure is implemented to sample the full entrance pupil.

A detector is positioned behind the SBA at the iSIM entrance pupil. It is a ZWO ASI6200 Pro, a low-noise 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 within the SBA. As detailed in the dedicated paper, the camera was calibrated in absolute units, yielding a conversion factor between DN/s and optical power of $2.5 \times 10^{-18} \text{ W}/(\text{DN/s})$ ¹⁰.

For the initial ARRAKIHS straylight measurements, an Akela TRIO-3LD17 laser operating at 808 nm was used. The iSIM will also be tested in the facility using the same laser and a 320-nm UV source, enabling straylight measurements for two spectral channels.

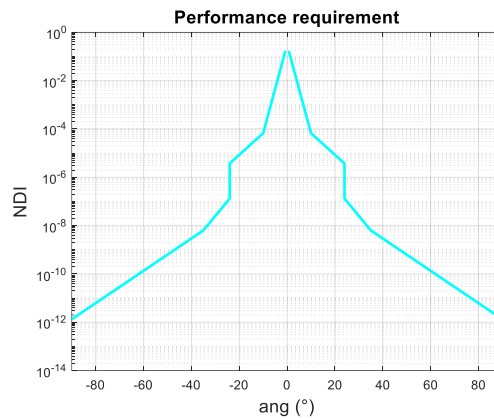


Figure 3-1: NDI performance requirement

MGSE configuration and scanning strategy

The scan of the baffle entrance is performed along both the short and long axes using the MGSE. The MGSE supports and positions the SBA and consists of a rotation stage, combined with two perpendicular 600-mm translation stages. Two MGSE configurations are foreseen: a vertical configuration, with the SBA mounted upright, and a horizontal configuration, shown in Figure 2-4.

Each configuration requires a dedicated mechanical interface for the SBA. Switching between them involves disassembling and realigning the interface. The entire MGSE is aligned using a laser tracker to ensure repeatability and geometric accuracy throughout the measurement campaign.

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 to monitor the 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 guarantees consistent test conditions across repeated scans of the entrance pupil. It also facilitates long-duration acquisitions required to measure extremely low straylight levels.

Test sequence

Both breadboards, BB#1 and BB#2, were tested in the horizontal configuration, corresponding to an azimuth of 0°. Several elevation angles were considered for these preliminary measurements.

Based on the AIV of the collimator OGSE and the MGSE elements, and using the laser-tracker metrology files, fine alignment corrections were considered when defining scanning positions for the MGSE.

For each elevation angle, a spatial scan of the baffle entrance is performed. At each spatial position, an image is acquired with the detector. The scan pattern is adjusted to avoid any overlap between successive images (considering a circular collimated beam that becomes an ellipse in the X–Y plane of the SBA reference frame). All images are then recombined by summation, excluding the spatial position where the beam directly reaches the detector without interacting with the baffle (i.e., the direct path through the aperture).

The NDI is computed at the center of the expected entrance pupil of the iSIM. A uniform NDI distribution across the pupil is assumed. The detector entrance pupil is 1 mm², due to a diaphragm placed in front of the camera. The collimator irradiance was determined during AIV. For this test, the laser diode was operated at 2 A with no attenuation filter, yielding an absolute irradiance of 14.601 W/m². The detector measures digital numbers (DN), which are normalized by the integration time (DN/s) and converted to optical power using the absolute calibration factor¹⁰.

Figure 3-2 illustrates, as an example, the scan pattern expressed in the SBA reference frame for an azimuth of 0° and an elevation of 5°. The green circle indicates the detector position in the SBA coordinate system.

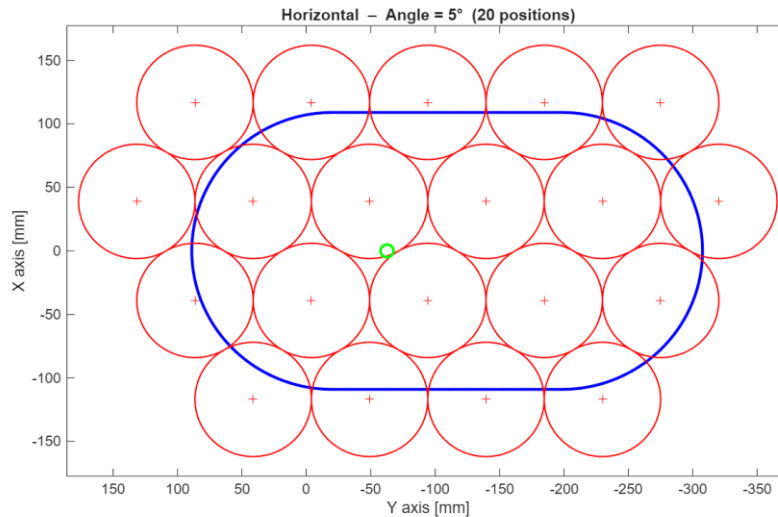


Figure 3-2: Scan pattern for an azimuth of 0° and an elevation of 5°, expressed in the SBA reference frame. The green circle represents the detector position, viewed in the SBA reference frame.

Test results

Figure 3-3 and Figure 3-4 show, respectively, for BE#1 and BE#2, the reconstructed image obtained by summing all contributions from the spatial scan at an elevation of -15°. The color scale represents $\log_{10}(\text{NDI})$, with a different dynamic range for each image to highlight the relevant features.

While the total reconstructed image is of interest, since it will be used in the next phase of the test campaign to compute the full NDI, examining individual scan positions is equally informative. At this high elevation angle (-15°), the vanes are clearly visible: they are illuminated by the collimated beam and scatter toward the detector. The two breadboards behave differently, as expected, but the general straylight pattern is identical. As a reminder, BE#1 is nearly uncoated, whereas BE#2 is fully black-anodized. The anodization reduces the NDI at the vane edges by one or two orders of magnitude. However, the black-anodized surface of BE#2 is relatively specular, producing localized bright spots at levels higher than those observed on BE#1. This behavior will require further analysis. Such specular features are expected to be less pronounced with black paint, such as Aeroglaze Z307.

A second example is shown at a smaller elevation angle (2°). Figure 3-5 and Figure 3-6 present scan position 8/13 for BB#1 and BB#2. At this angle, the vanes are no longer visible for BB#2 while being predominant for BB#1. The improved scattering performance is clearly highlighted, with a gain of one or two orders of magnitude.

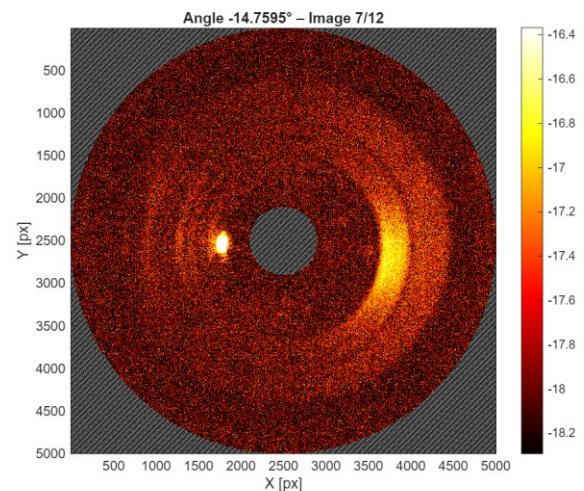
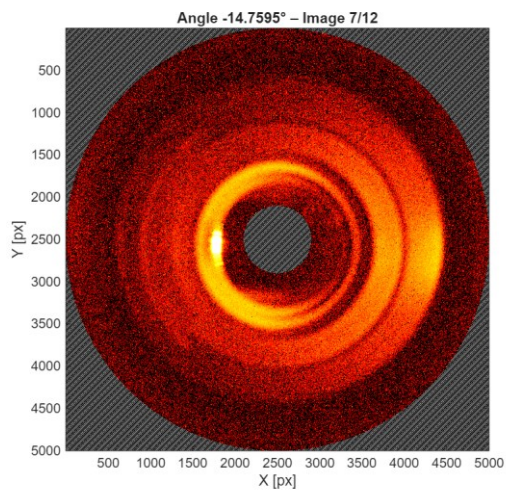
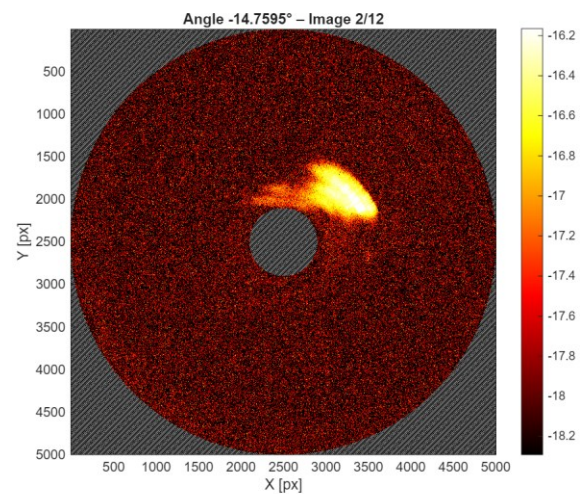
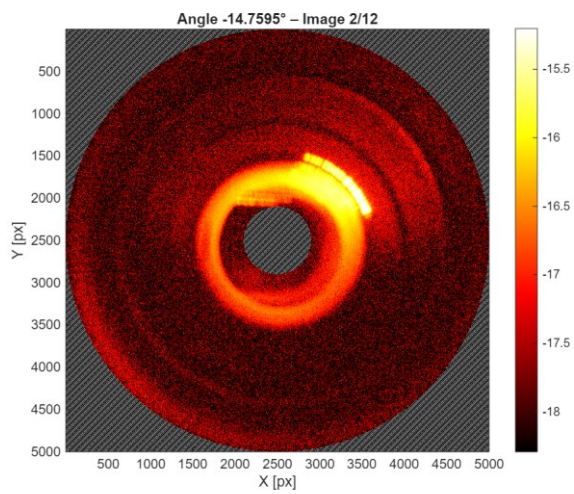
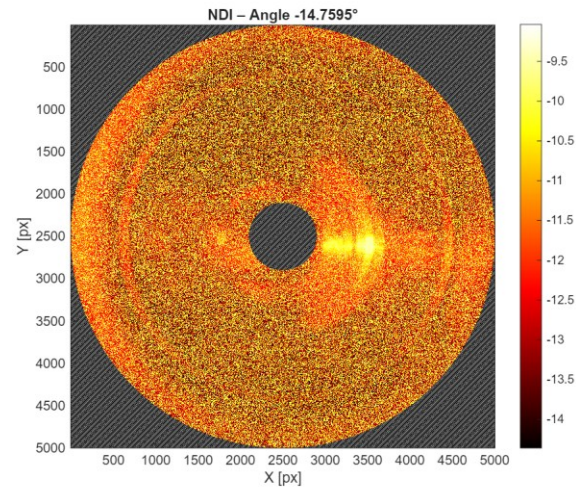
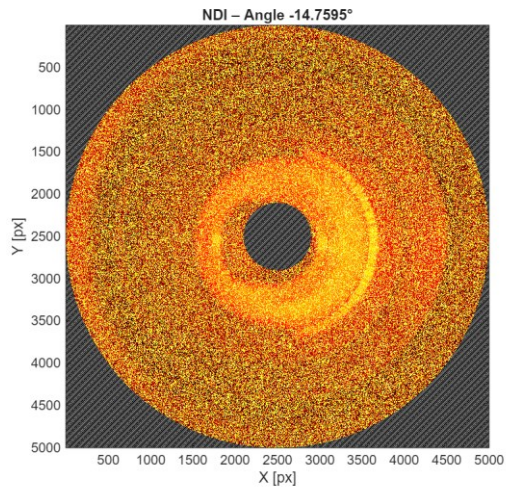


Figure 3-3: BB#1 at elevation -15°. Total NDI (top), scan 2/12 (middle) and 7/12 (bottom).

Figure 3-4: BB#2 at elevation -15°. Total NDI (top), scan 2/12 (middle) and 7/12 (bottom).

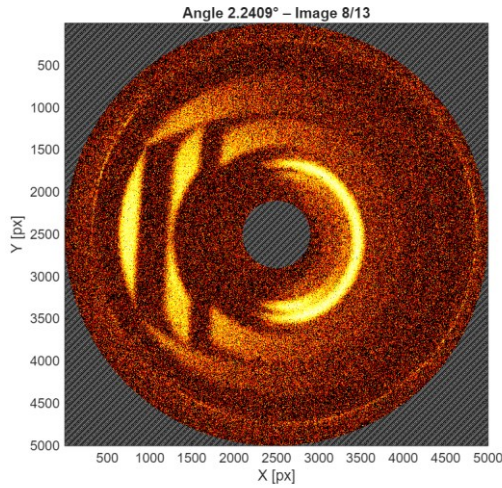


Figure 3-5: BB#1 at elevation 2°. Scan 8/13.

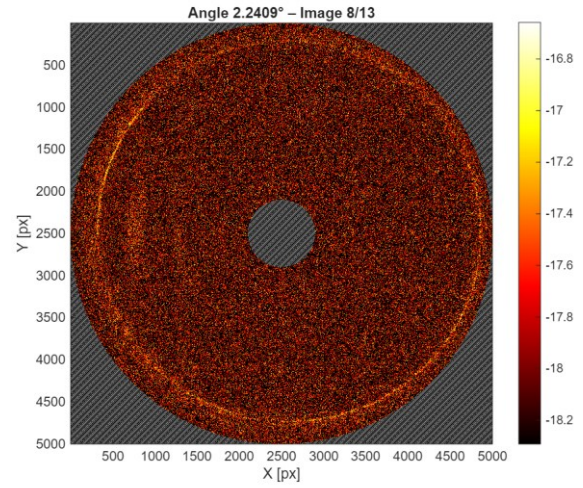


Figure 3-6: BB#2 at elevation 2°. Scan 8/13.

4. SOFTWARE STRAYLIGHT ANALYSIS

Straylight model

In parallel with the breadboard test campaign, a software straylight analysis of the full payload is being conducted to validate the SBA design against the mission-level NDI requirement and, ultimately, to compare the ray-tracing predictions with the laboratory measurements presented in Section 3.

The model reproduces one binocular of the instrument, comprising the two iSIM channels (primary mirror M1, secondary mirror M2, field lens FL and detector FPA), the fold mirror (FoM), one SBA, the surrounding mechanical structures (iSIM housing, instrument box, FPA mount) and the sunshield antennas, as shown in Figure 4-1. Optical surfaces are characterized by a specular component, a roughness-driven scatter term (1 nm RMS for all iSIM and SBA optics), and a particulate contamination level ranging from 600 ppm to 1400 ppm, depending on the surface, in accordance with the MIL-1246C/TEST-STD-1246D cleanliness classes. Black-coated mechanical parts (baffles, housing, box) are modeled with black anodization or MAP black-paint scatter properties. The analysis currently focuses on the VIS2 channel; the VIS1 and NIR channels will be included in a future model update.

The source is a 1 W elliptical beam that matches the SBA entrance aperture (semi-axes of 140 mm and 236 mm), corresponding to an irradiance of 9.63×10^{-6} W/mm² at the SBA entrance, and is used as the reference for all NDI computations.

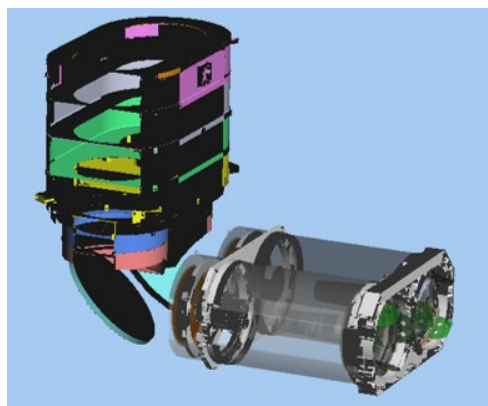


Figure 4-1: Straylight model of one binocular and the SBA.

Analysis cases

NDI curves are computed as a function of field angle, both in-field (0° and $\pm 0.65^\circ$ along the short and long axes) and out-of-field, up to $\pm 80^\circ$. For each FOV point, the following contributions are analyzed separately and then compared:

- ghost reflections on the iSIM optics and detector, without scattering
- ghost reflections combined with a single scattering event on the FoM
- single scattering on the iSIM optics, and separately on the iSIM mechanics (M1/M2 baffles and iSIM tube);
- single scattering on the FoM alone
- double scattering combining the FoM and the iSIM optics
- triple-scattering paths involving two bounces inside the SBA followed by a scattering event on either the FoM or the iSIM optics

Scattering from the SBA vane edges is being analyzed as dedicated, localized straylight paths and is treated separately from the systematic FOV scan.

Preliminary results

Simulations are ongoing. Preliminary results indicate that ghost reflections dominate the straylight budget near the field edge, with an average NDI about one order of magnitude above that from single-scattering mechanisms, and remain the largest contributor even when combined with FoM scattering. Scattering on the iSIM optics and on the FoM alone contribute at comparable levels. iSIM mechanics scattering is roughly two orders of magnitude lower, with essentially no scattered ray reaching the detector at 0° FOV. Combining two scattering events (FoM followed by iSIM optics) reduces the average NDI by a further two orders of magnitude relative to either single-scattering case, although the associated maximum NDI remains comparatively high, indicating a localized rather than diffuse contribution.

Straylight paths requiring two internal bounces inside the SBA before reaching the FoM (three scattering events in total) are roughly five orders of magnitude below the FoM+iSIM optics double-scattering case, with a maximum NDI around 6×10^{-8} . For all scattering-dominated cases, the NDI is not symmetric with respect to the FOV sign, with higher levels systematically observed for negative field angles along the long axis, a signature of the SBA's internal geometry.

These preliminary simulations are related to the full optical payload. For the SBA, the simulations will be refined to confront the straylight measurements described in Section 3 once the full FOV scan is completed. The illumination setup from the measurement facility will be modeled in a simulated environment to validate the model. This will support the assessment of the SBA's performance against the mission requirement.

5. CONCLUSION

The development and verification of the ARRAKIHS straylight baffle assembly constitute a key step. Two representative breadboards were manufactured and tested in a newly developed straylight facility at CSL, enabling controlled illumination, precise scanning, and absolute irradiance measurements. The first experimental results demonstrate clear differences between the two breadboards, confirming the impact of surface treatments on straylight rejection.

In parallel, a straylight model of the full payload is being developed to assess the contribution of optical and mechanical elements. Preliminary simulations identify ghost reflections as the dominant straylight mechanism near the field edge, with scattering contributions following expected trends for the iSIM optics, fold mirror, and internal baffles. These results will be confronted with laboratory measurements, providing a combined experimental–numerical validation of the payload design.

The ongoing work will support the consolidation of the straylight budget for ARRAKIHS and guide the final design choices for the flight model. Future activities include extended measurements on both breadboards, coating comparison, and straylight measurement of the iSIM. Together, these efforts will ensure that the payload meets the mission-level NDI requirement and achieves the sensitivity needed to detect the faint structures targeted by ARRAKIHS.

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