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ABSTRACT

The Solar Orbiter/Metis visible and UV solar coronagraph redefines the concept of external occultation in solar coronagraphy. Classical externally occulted coronagraphs are characterized by an occulter in front of the telescope entrance aperture. Solar Orbiter will approach the Sun down to 0.28 AU: in order to reduce the thermal load, the Metis design switches the positions of the entrance aperture and the external occulter thus achieving what is called the inverted external occultation. The inverted external occulter (IEO) consists of a circular aperture on the Solar Orbiter thermal shield that acts as coronagraph entrance pupil. A spherical mirror, located 800 mm behind the IEO, back rejects the disk-light through the IEO itself. To pursue the goal of maximizing the reduction of the stray light level on the focal plane, an optimization of the IEO shape was implemented.

The stray light calibration was performed in a clean environment in front of the OPSys solar disk divergence simulator (at ALTEC, in Torino, Italy), which is able to emulate different heliocentric distances. Ground calibrations were a unique opportunity to map the Metis stray light level thanks to a pure solar disk simulator without the solar corona. The stray light calibration was limited to the visible light case, being the most stringent. This work is focused on the description of the laboratory facility that was used to perform the stray light calibration and on the calibration results.

Keywords: Stray light, solar coronagraph, Solar Orbiter, Occulter Apodization, Calibrations

1. INTRODUCTION

Metis^{1,2,3} is an externally occulted solar coronagraph that will fly aboard the space mission Solar Orbiter.⁴ Metis can simultaneously image the visible (measurements of the linear polarization in the visible band 580-640 nm) and ultraviolet emission of the solar corona (images of the UV corona in a 10 nm narrow band centered on the HI Ly- α 121.6 nm line) and diagnose, with unprecedented temporal coverage and spatial resolution the structures and dynamics of the full corona in the annular field of view (FOV) from 1.6° to 2.9°. Metis will deal with challenges that no coronagraph faced before.

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The mission peculiar characteristic is the orbit: it will approach the Sun down to a perihelion of 0.28 AU and will go out of the ecliptic up to an inclination of 34° . A heat shield is protecting the spacecraft and the 10 instruments of the scientific payload. Imaging instruments such as Metis, as they must look through the heat shield, have to deal with the huge thermal loads as a consequence of the closeby Sun. In order to reduce the thermal load inside the coronagraph and preserve the FOV, Metis adopts an innovative occultation solution, which is based on switching positions between entrance aperture and occulter.⁵ The entrance aperture is called inverted external occulter, IEO, and is actually the diaphragm which receives the direct solar disk light. The M0 spherical mirror, positioned 800 mm behind the IEO, back-reflects the solar disk by focusing its image on the IEO itself, as shown in **Figure 1**.

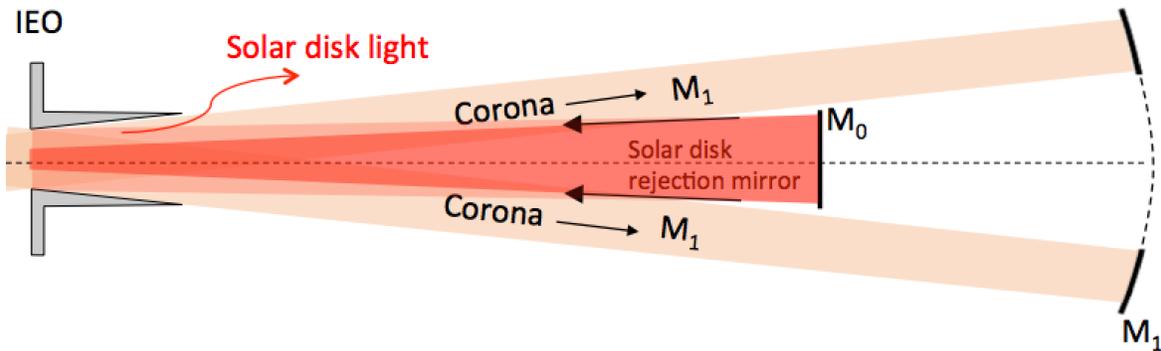


Figure 1: Inverted external occulter (IEO) scheme (not-to-scale).

The complete scheme of the Metis optical design is depicted in **Figure 2**. The coronal light is collected by the telescope, which is an on-axis Gregorian. The telescope optics are shared by the UV and the visible light (VL) channels. The interferential filter (IF) acts as a beam splitter by separating the UV from the visible light (VL) channel. The UV light is let through and is collected by the UV detector assembly (UVDA). The VL is reflected through the polarimeter towards the VL detector assembly (VLDA). Stray light minimization is a mandatory goal in any coronagraph, due to the extreme high contrast between the solar photosphere and the corona (> 6 orders of magnitude). The worst offenders to the stray light level on the instrument focal plane are the surfaces hit by the direct solar disk light, IEO and M0. Actually, the M0 edge is in the shadow of the IEO edge, thus its contribution is expected to be lower. The internal occulter (IO) is conjugated to the IEO with respect to the primary mirror M1 and blocks the solar disk light diffracted by the IEO edge. The IO axis alignment with the telescope optical axis can be fine-tuned on ground and in flight by means of an XY motorized stage (the movements are on the plane perpendicular to the optical axis). The Lyot stop (LS) is conjugated to M0 and is designed to block the light diffracted by the M0 edge. The field stop (FS) identifies the primary focal plane and limits the outer FOV of the coronagraph.

Alike all preceding externally occulted coronagraphs,⁶ the IEO needs an apodization of the occulter shape in order to further reduce the stray light level.

For METIS the requirement is that the stray light shall be less than 10^{-9} in units of mean solar disk brightness in the VL wavelength range.⁷

A long and truly accurate measurement campaign was conducted with a Metis occulting system prototype, BOA (Breadboard of the Occulting Assembly), in order to define the type and the characteristics of the IEO apodization.⁸

The IEO is an inverted truncated cone (see its section in Figure 1) with a semi-divergence angle of 1.07° , a front aperture diameter of 40 mm and a length of 30 mm. The choice of a polished conical surface is a first for a coronagraph, both for the inversion of the occulter and for the apodization shape (SOHO/LASCO C2,⁹ which is the closest in concept, implements a multi-threaded truncated cone). Thus, the stray light calibrations are significant not only to verify the instrument compliance with the requisite, but also to validate the innovative apodizing choice.

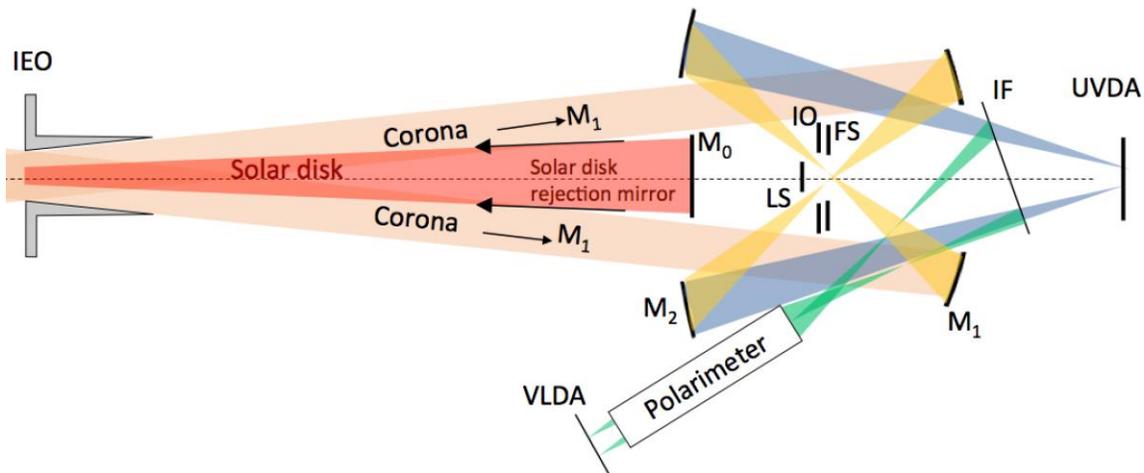


Figure 2: Schematic view of the Metis optical design (not-to-scale).

The integration and the on-ground calibrations were performed at the Optical Payload System (OPSys), a laboratory of the INAF Astrophysical Observatory of Torino hosted by ALTEC S.p.A. in Torino (Italy),¹⁰ in an ISO5 environment in front of a solar divergence simulator. Section 2 describes the experimental setup and the adopted equipment. Section 3 is dedicated to the data analysis description. Results are presented and discussed in section 4.

2. CALIBRATIONS EXPERIMENTAL SETUP

The OPSys facility is constituted by three communicating clean rooms which host the SPOCC (Space Optics Calibration Chamber), as shown in **Figure 3**.

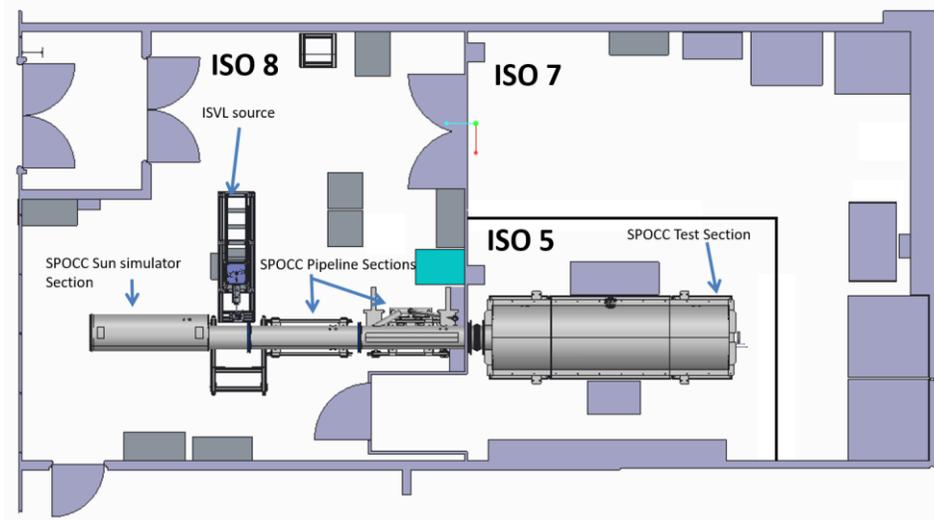


Figure 3: Scheme of the OPSys facility with the SPOCC.

SPOCC is a solar divergence simulator that can operate in air and in vacuum, in order to perform tests in the UV. It comprises three main sections:

- The test section: a chamber characterized by a semi-cylindrical cover that can be removed in order to access the optical bench. This section is installed inside an ISO5 clean room. The stray light calibration was performed in air on the SPOCC bench (without cover).
- The pipeline section: it is made of three sub-sections in order to change the pipeline length upon need. One of the three sub-sections is interfaced with the test section inside the ISO5 clean room. The remaining parts of the tube, where the pumping system is installed, are located in the ISO8 clean room. The length used for the stray light calibration was about 5 m.
- The solar disk divergence-simulator section: constituted by the source, the solar disk diaphragm, a folding mirror and the collimator. The source is the ISVL (Illumination System for Visible-light), a stabilized arc-lamp with a dedicated optics that simulate the limb darkening of the real photosphere.¹¹

The stray light calibration was performed in VL only, being the VL channel the most critical in terms of stray light rejection. Metis channels share the same optics, thus a matched requirement in the VL implies a similar result in the UV.

The SPOCC optical bench can be tilted in pitch and yaw by means of a dedicated motorized system. The tilt is needed during the off-pointing stray light measurements.

The solar simulator can reproduce different solar dimensions, down to an equivalent heliocentric distance of 0.5 AU. Being the largest available solar dimension, 0.5 AU was the heliocentric distance at which the most significant stray light image was taken. Images were taken at 1.0 AU as well.

A ray tracing of the solar simulator collimator is overlapped to a 2D CAD of the SPOCC in Figure 4 (a). The 45° folding mirror of Figure 4 (c) is needed in order to allow the ISVL positioning in the ISO8 clean room.

The SPOCC collimator is surrounded by a light trap, which, from the Metis point of view, simulates a dark solar corona. The light trap is shown in Figure 4 (b).

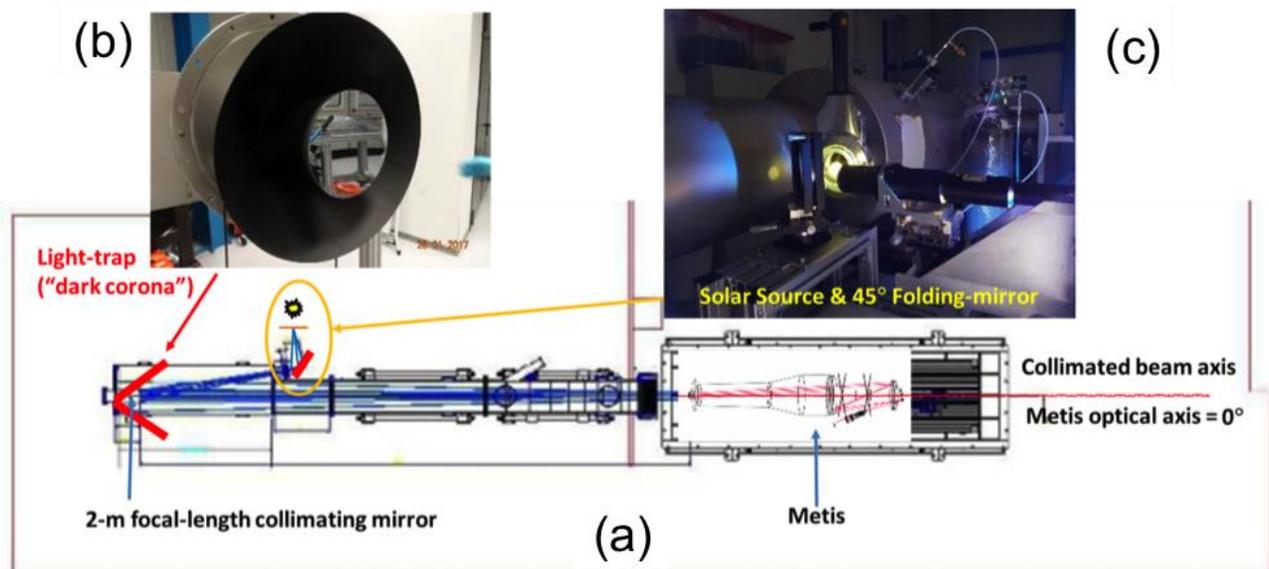


Figure 4: (a) Ray tracing overlapped to the SPOCC 2D CAD and Metis positioned on the test section bench. (b) Light trap around the collimator. (c) ISVL and folding mirror.

A picture with Metis on the SPOCC optical bench is shown in Figure 5. The exit aperture of the SPOCC pipeline can be seen on the right hand side.

Before the stray light calibration, the laboratory underwent a thorough light tightening optimization: all the spurious sources were obscured and the inner parts of the SPOCC pipeline that might have contributed to the stray light were, if accessible, blackened.



Figure 5: Metis on the SPOCC optical bench.

3. DATA ANALYSIS FLOW

To check the stray light requirement (see section 1), the stray light images shall be normalized to the mean solar disk, as if it was imaged on the focal plane by the Metis optics in absence of occultation system. It is directly not achievable in practice, being the coronagraph integrated and aligned, thus a workaround had to be considered. For this, Metis was off-pointed until a solar disk image was detected. Then, the image was calibrated by means of the vignetting map of the telescope, in order to retrieve what would have been detected without occulting system.

Unfortunately, a direct, off-pointed, solar disk image cannot be taken with Metis and the ISVL. In fact, the ISVL source brightness cannot be tuned and it would saturate the Metis detector if directly imaged onto the focal plane. So, the solar disk images were taken with a tunable LED source, much less bright than the ISVL. A calibrated photodiode with a Metis visible pass-band filter was used in order to inspect the irradiance entering the IEO aperture in both cases, ISVL and LED source.

By calling SL the stray light image acquired with the exposure time Δt_{SL} and I_{Sun} the mean solar disk irradiance in digital numbers per second (DN/s) on the visible focal plane, we may write the normalized stray light as:

$$SL_N = \left[\frac{SL - BG_{SL}}{\Delta t_{SL}} \right] / I_{Sun} \quad (1)$$

Where BG_{SL} is the background (i.e., a dark frame) with the exposure time Δt_{SL} .

While the numerator of equation (1) is straightforward, the measurement of I_{Sun} is a bit more complex. It is measured as an average over the solar disk image as if no occulting system was present.

As anticipated at the beginning of this section, the solar disk image (and thus the I_{Sun} value) is taken with a LED source in place of the ISVL (used instead for acquiring SL) and with Metis in off-pointing. Thus, a cross calibration has to be performed with the photodiode data in order to account for the different source intensities and a normalization to the vignetting map has to be made to consider the off-pointing. The remaining part of this section is dedicated to the description of the procedure followed to obtain I_{Sun} .

The solar disk image in DN/s as it was generated by the ISVL source can be obtained as:

$$FS_{ISVL} = \left[\frac{FS_{LED} - BG_{LED}}{\Delta t_{LED}} \right] \cdot \frac{I_{ISVL}}{I_{LED}} \quad (2)$$

Where FS_{LED} is the solar disk image obtained with Metis in off-pointing and the LED source, its exposure time being Δt_{LED} ; BG_{LED} is the background with the exposure time Δt_{LED} ; I_{LED} and I_{ISVL} are the photodiode detected currents in case of LED and ISVL sources, respectively.

The image FS_{ISVL} is shown in Figure 6 (a) in case of a simulated heliocentric distance of 0.5 AU.

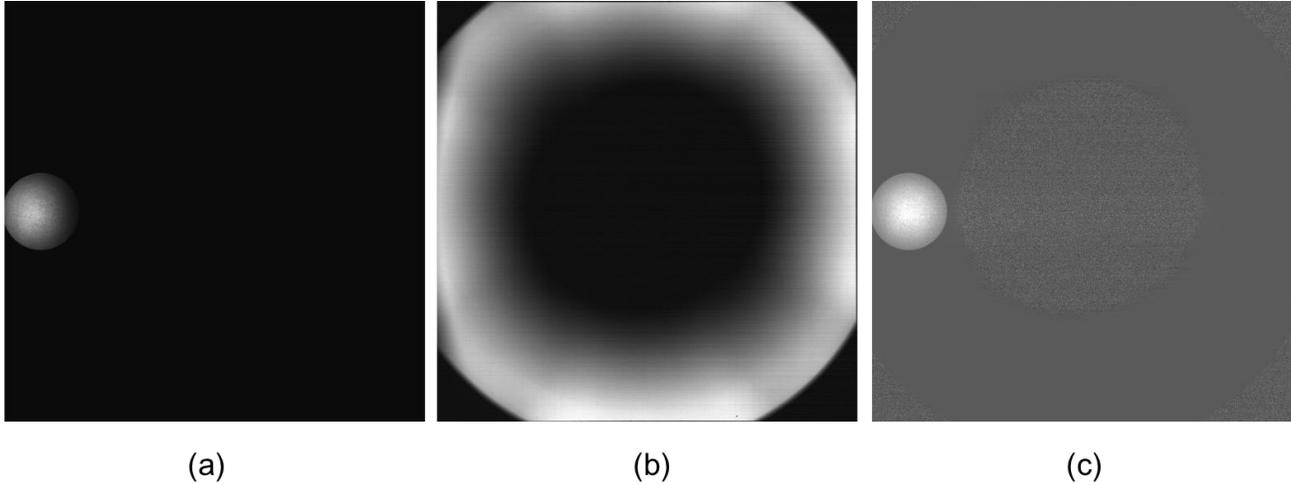


Figure 6: (a) Solar disk image with Metis in off-pointing as obtained with the operation described by equation (2), with a simulated heliocentric distance of 0.5 AU. (b) Vignetting map. (c) Solar disk image calibrated by using the vignetting map.

The solar disk intensity is not showing radial symmetry because of the telescope vignetting. In order to obtain the image as it was taken without occulting system, FS_{ISV} shall be normalized to the vignetting map.

In order to retrieve the vignetting map, a LED flat field source was used in front of the IEO. The spatial irradiance uniformity of the flat field source is >96%. The flat field image which provides the vignetting map is given by:

$$FF_D = \frac{FF - BG_{FF}}{\Delta t_{FF}} \quad (3)$$

where FF is the flat field image taken with the exposure time Δt_{FF} and BG_{FF} is the relative background. FF_D is shown in Figure 6 (b).

Due to the Metis radiometric calibration results, it is not possible to disentangle the vignetting function from the instrument throughput. In order to access the percent vignetting map, we take into account the theoretical vignetting function as simulated with Zemax OpticStudio®, $f(r)$. The percent vignetting map is then obtained as:

$$FF_{\%} = FF_D \times \frac{Max(f(r))}{Max(FF_D)} \quad (4)$$

where the $Max()$ operator provides the maximum value.

By using equation (4) it is possible to normalize FS_{ISVL} . The resulting image is given by:

$$FS_V = \frac{FS_{ISVL}}{FF_{\%}} \quad (4)$$

and is shown in Figure 6 (c). The solar disk image intensity has now a radial symmetry. The average over a region of interest (ROI) that selects the solar disk only provides I_{Sun} .

4. STRAY LIGHT RESULTS

Metis stray light was evaluated at 0.5 and 1.0 AU with Metis aligned to the simulated Sun. At a simulated heliocentric distance of 0.5 AU and with Metis aligned to the Sun, the IO position was finely tuned in order to minimize the stray light level on the VL focal plane. Then, off-pointing measurements were performed at 0.5 AU.

The following sections account for all the measurements.

4.1 IO fine tuning

At a simulated heliocentric distance of 0.5AU, which corresponds to the largest solar disk that can be collimated by the SPOCC, the IO position fine-tuning was performed.

After Metis integration and alignment, without IO fine-tuning, the stray light image was somehow alarming. It is shown in Figure 7. The color scale maximum value is forced to the requisite.

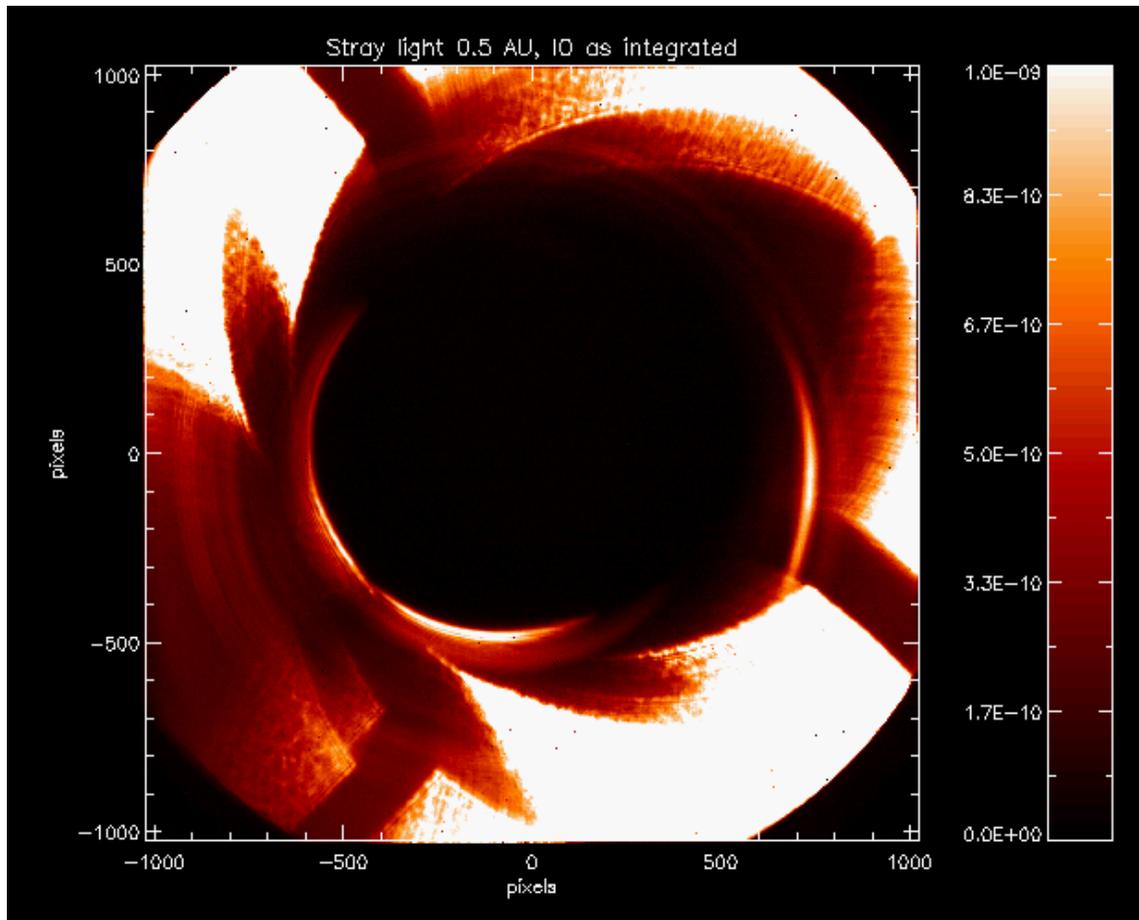


Figure 7: Stray light image before the IO position fine-tuning. Simulated heliocentric distance: 0.5 AU.

The stray light requisite was not respected for a large part of the image. Then, a step-by-step optimization of the IO position was performed. The stray light variations from a movement to the next were quantitatively evaluated by averaging the signal detected in the 4 ROIs shown in color in Figure 8. ROIs have been selected in order to encompass

the image of the IO edge and are relative to the 4 sectors defined by the two motors orientation and direction (which are shown as well by arrows in the figure). In Figure 8, Y orientation and direction-related ROIs are represented with solid lines, X orientation and direction-related ROIs with dashed lines.

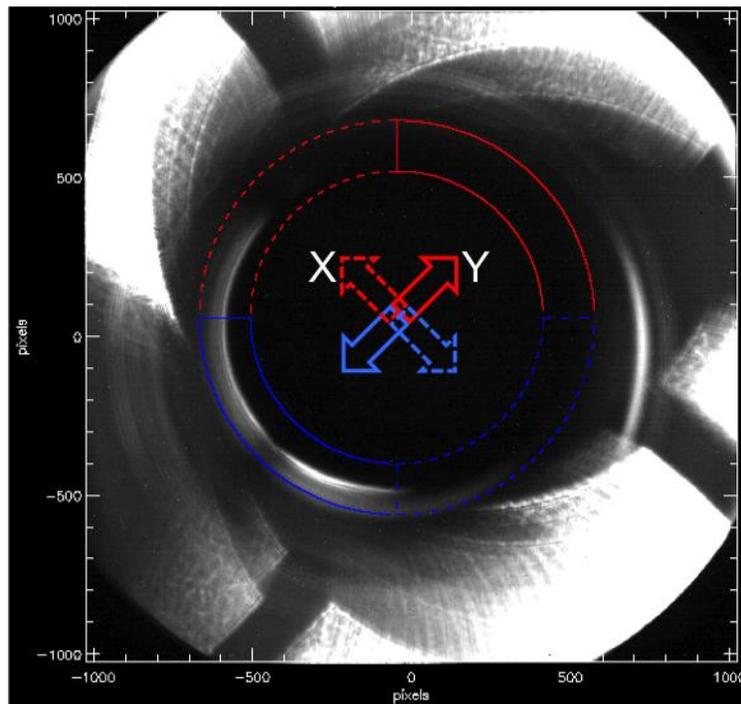


Figure 8: ROIs to quantitatively evaluate the IO movements. The X and Y IO motor direction are shown as well.

By keeping the Y motor fixed and moving the X motor we evaluated the average signal in the two dashed line ROIs shown in Figure 8. The obtained result is shown in Figure 9.

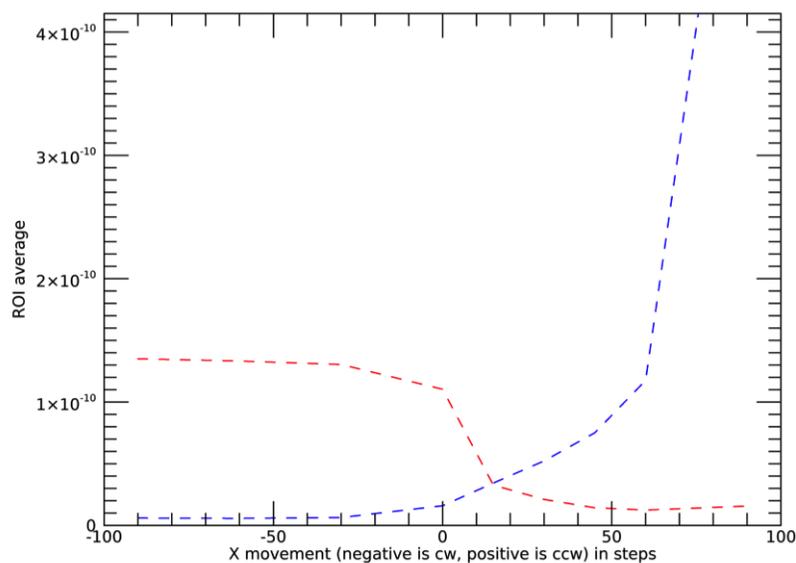


Figure 9: ROI average signals relative to the X movement of the IO motor. The red and blue colors refer to the two different colored dashed lined ROIs shown in Figure 8.

The two ROIs average signals (corresponding to the positive and to the negative X motor movements) are balanced when the X motor is tuned to +10 steps.

By keeping the X motor fixed at +10 and moving the Y motor we evaluated the average in the two solid line ROIs shown in picture Figure 8. The result is shown in Figure 10.

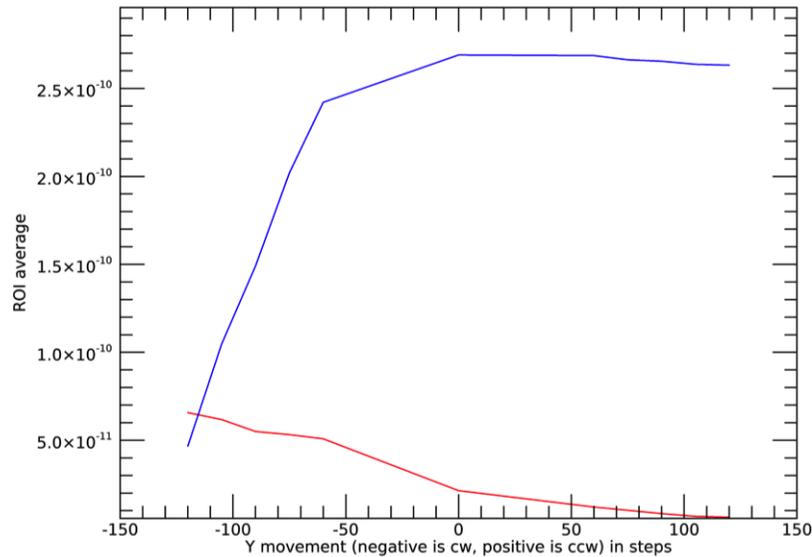


Figure 10: ROI averages relative to the Y movement of the IO motor. The red and blue colors refer to the two different colored solid lined ROIs shown in Figure 8.

The two ROIs average signals (corresponding to the positive and to the negative Y motor movements) are balanced when the Y motor is tuned to -120 steps.

With the new fine-tuned IO position, a new stray light image was taken. It is shown in Figure 11.

The stray light level is well within the requirement for the whole corona, except for a saturated area at the upper edges and a small crescent moon at half the FOV. Both features -which are in any case slightly exceeding the stray light limit requirement (both below 1.6E-9 in mean solar disk brightness units)- are due to the experimental setup, being generated by the ISVL light scattering off the pipeline internal structure. In order to come to such a conclusion, a simulation was performed with a 3D CAD of the SPOCC pipeline, shown in Figure 12 (a). The vacuum flanges (for gauges or pumps) are emphasized in red, the exit aperture flange is in blue and the turbo-molecular pump is in green. A camera with the same focal length of Metis and a comparable FOV was positioned in the 3D CAD at the same distance of Metis from the exit aperture of the SPOCC pipeline. The image taken by the simulated camera is shown in Figure 12 (b).

The image has been vertically flipped so to match the orientation of the METIS visible channel detector. The central light blue circle is the SPOCC collimator. The green corona around the collimator is the light trap, which is completely blackened. The big grey ring is a SPOCC pipeline baffle, which is opportunely blackened in the real pipeline.

The two greyish elements with the shape of a crescent moon are vacuum flange apertures that are not blackened. The flanges generate a light scattering that can be seen by Metis and results in the two bright features of Figure 11. Some stray light is due to the solar disk light reflected by M0 and back scattered by the pipeline baffles, but the contribution is well below the specification. The morphological explanation of the most evident stray light features of Figure 11 is shown in Figure 13.

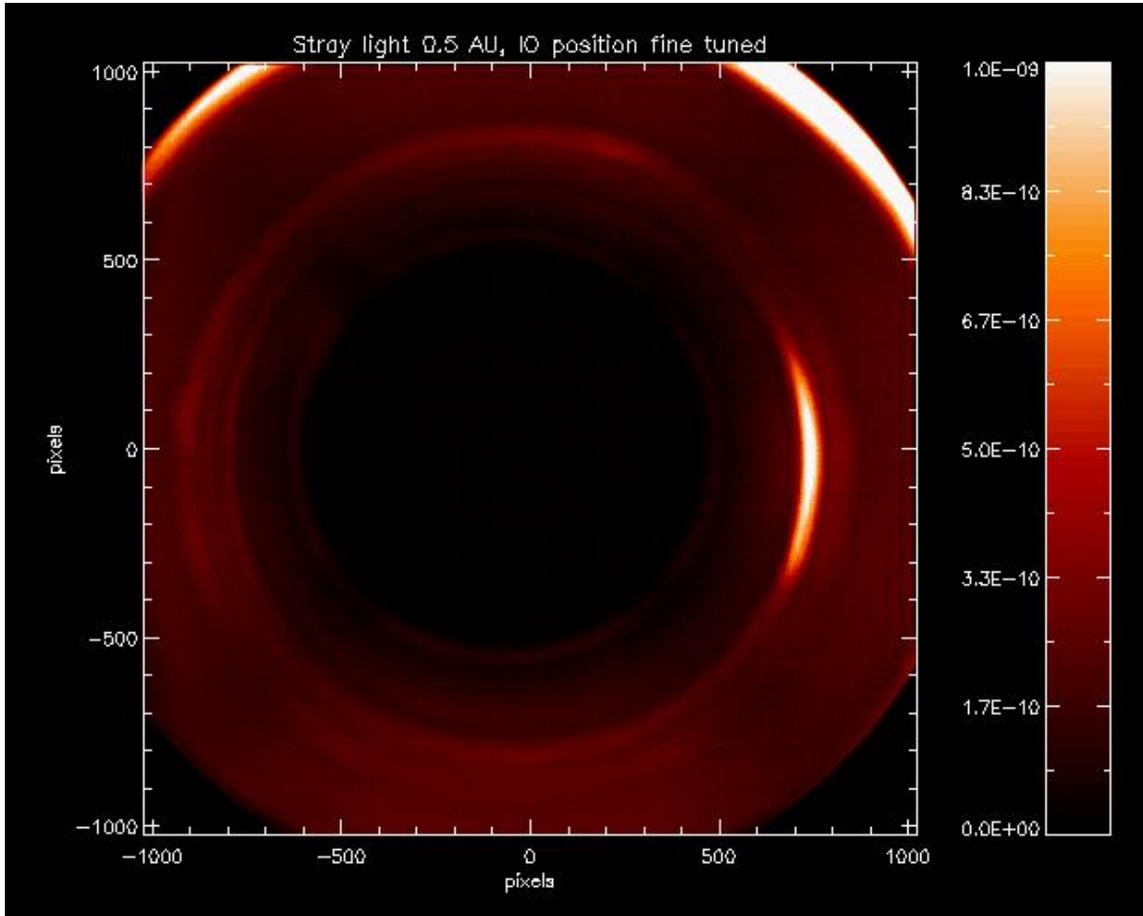


Figure 11: Stray light image after the IO position fine-tuning. Simulated heliocentric distance: 0.5 AU.

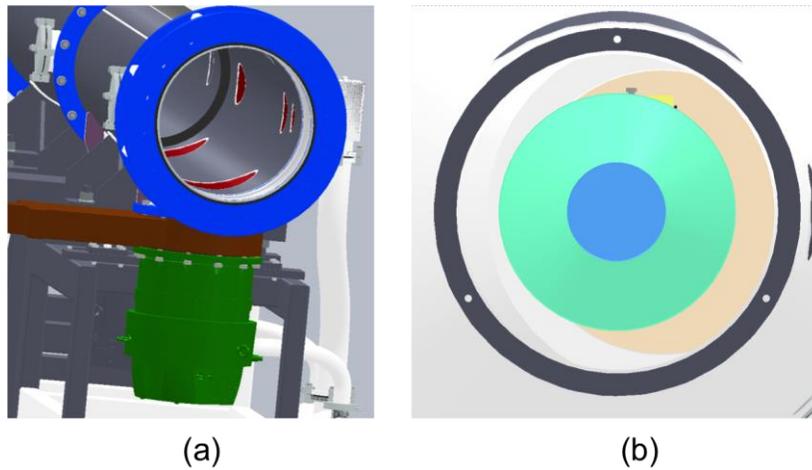


Figure 12: (a) Particular of the 3D CAD of the SPOCC pipeline. In blue the exit aperture flange, in red the vacuum flanges, in green the turbo molecular pump. (b) Image taken with a simulated camera with the Metis characteristics placed at the same distance of Metis from the pipeline exit aperture in the 3D CAD. See text for description.

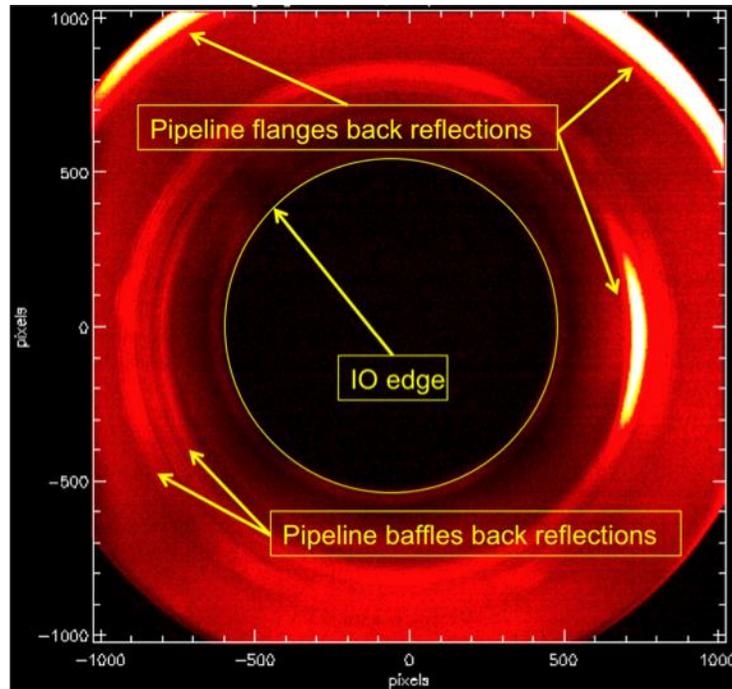


Figure 13: Morphological analysis of the bright features that can be identified in Figure 11.

4.2 Stray light at 1.0 AU

Being the SPOCC able to simulate solar disk divergences correspondent to different heliocentric distances, beyond the main stray light test at 0.5 AU, we evaluated the Metis stray light also at 1.0 AU.

The procedure to process the image is described in section 3. The result, obtained after the IO fine-tuning described in section 4.1, is shown in Figure 14.

As expected, the stray light is much lower with respect to the case at 0.5 AU (see Figure 11). The features described in section 4.1 and shown in Figure 13 are still visible, despite at a lower brightness.

4.3 Off-pointing

Metis may experience off-pointings, due to spacecraft misalignments or to commanded operations.

It is interesting to understand whether Metis off-pointing (spacecraft + instrument off-pointing) can be estimated from asymmetries of the stray light pattern. It may be a crucial calibration for Metis in order to define the S/C boresight when sun-centered .

By taking advantage of the motorized SPOCC bench (see section 2), off-center acquisitions were performed at a simulated heliocentric distance of 0.5 AU with the fine-tuned IO. The off-pointing was investigated in yaw only, being the nominal Metis image circularly symmetric. The tested yaw tilt angles are: -0.6° , -0.3° , 0.3° , 0.6° .

In order to propose a potential operative method to infer misalignment information from the stray light image, we evaluated the behavior of the signal average with the off-pointing in 16 ROIs distributed over the image: ROIs are aligned with the Metis sectors, then each sector is split in 2 parts of equal radius range. ROIs are shown in Figure 15.

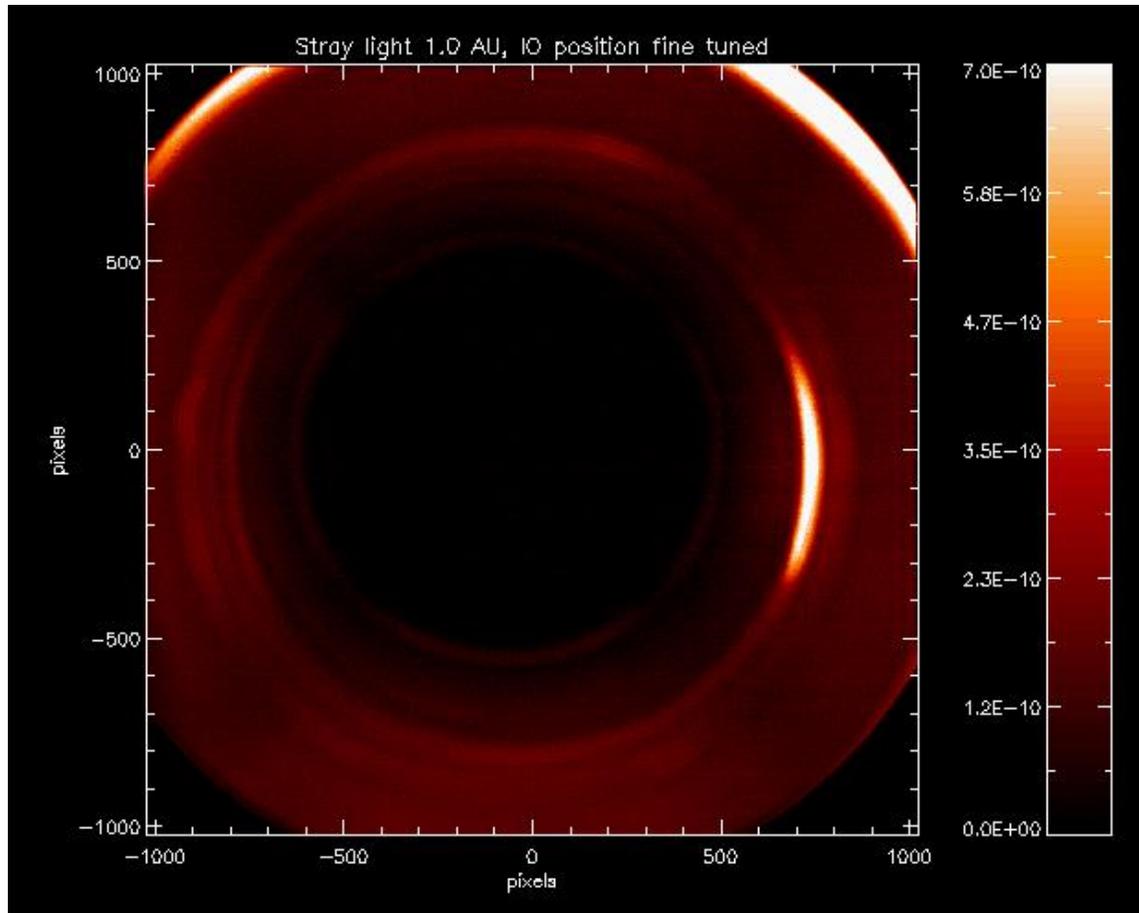


Figure 14: Stray light image after the IO position fine-tuning. Simulated heliocentric distance: 1.0 AU.

The plot in Figure 16 summarizes the result. The highest variation is obtained for ROIs 5 and 8 OUT, but those regions likely contain a contribution of setup stray light, which makes them not entirely reliable. ROIs 6 and 7 OUT are more reliable because less affected by the setup stray light. They show a behavior consistent with the off-pointing of the instrument with respect to the solar disk. Such a diagnostic strategy, opportunely refined, can be used in flight to monitor the spacecraft off-pointing.

In flight, the solar corona will be overwhelming the stray light. In order to adopt a similar approach to that described here, running difference images shall be utilized.

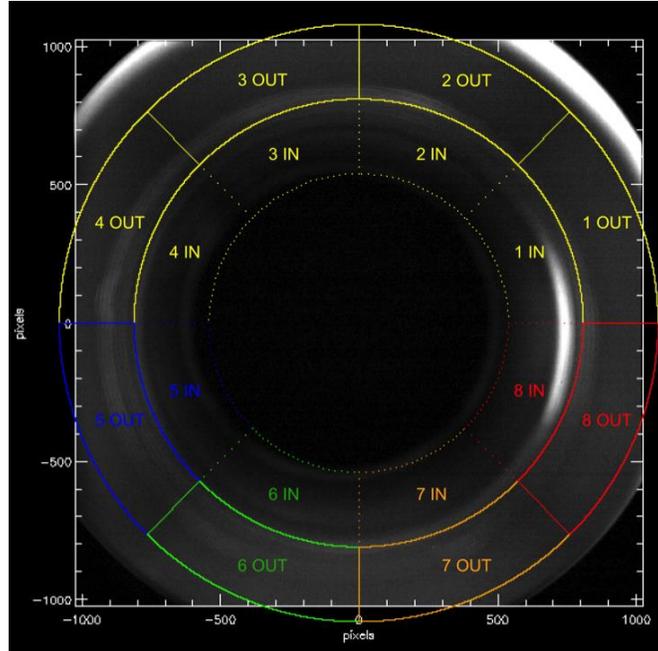


Figure 15: Set of ROIs for the off-pointing stray light variation evaluation.

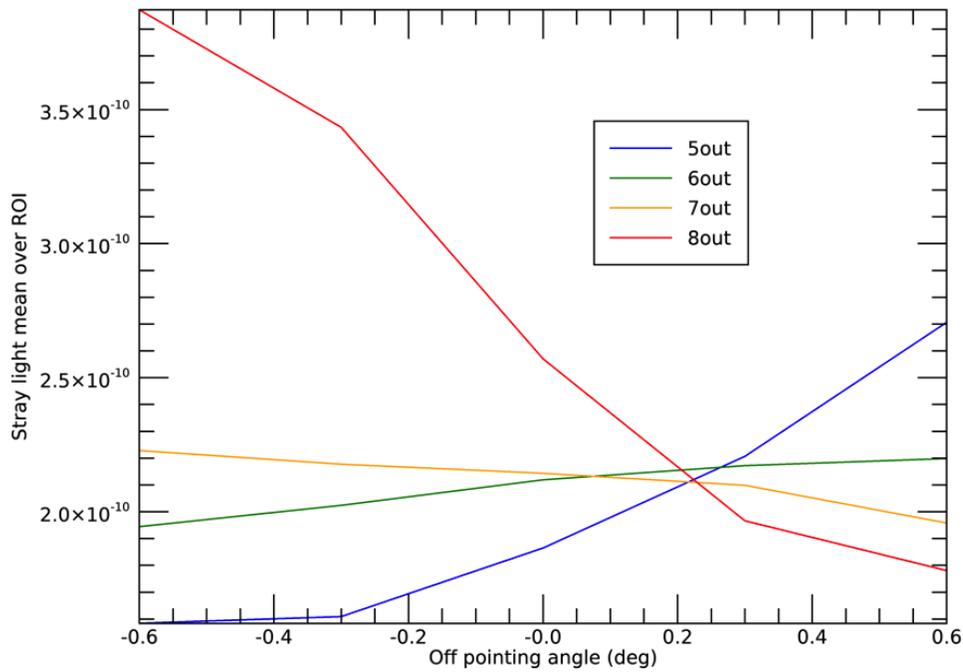


Figure 16: Variation of the stray light averages over ROIs 5, 6, 7, and 8 OUT (see Figure 15) as a function of the off-pointing angle.

5. CONCLUSIONS

This work reports on the on-ground stray light calibrations of Metis, an externally occulted solar coronagraph part of the scientific payload of the Solar Orbiter mission. Metis will perform measurements of the linear polarization in the visible light band 580-640 nm and narrow-band imaging in the HI Ly- α 121.6 nm line. Visible and UV share the same optical path, an interferential filter beyond the secondary mirror splits the channels.

The Solar Orbiter peculiar characteristic is the orbit, which will be out of the ecliptic and with a perihelion of 0.28 AU.

Solar Orbiter instruments, imagers in particular, will experience prohibitive environmental conditions. Metis optical design is suitable to face such conditions. Its innovative occultation concept, based on the inversion of the entrance aperture and the actual occulter, is adopted in order to keep a low thermal load while preserving the instrument FOV. The inverted external occulter is actually the entrance aperture of the instrument. The solar disk light is reflected out of the instrument by the M0 spherical mirror.

As all preceding externally occulted coronagraphs, Metis needs an apodization of the IEO in order to reduce the stray light.

After a long experimental campaign, the IEO was defined as an inverted truncated cone. The stray light calibration was a unique opportunity to prove the validity of the apodization choice and to verify the compliance with the stray light requirement. The requirement was to ensure that the stray light on the visible focal plane is lower than 10^{-9} in units of mean solar disk brightness.

The stray light calibration was performed at the OPSys facility hosted by ALTEC S.p.A. in Torino (Italy), in an ISO5 environment in front of a solar divergence simulator able to mimic different heliocentric distances.

Stray light images were taken at simulated heliocentric distances of 0.5 AU and 1.0 AU. The most critical in terms of stray light was the closest to the Sun. Metis is proved to be compliant to the stray light specification for a large part of the image: two small bright features slightly exceed the stray light limit and are due to scattering from the experimental setup.

The stray light measurements at 0.5 AU were used to fine-tune the position of the internal occulter (IO), which is mounted on a precision XY motorized stage. IO is designed to block the diffraction generated by IEO (that is the highest contributor to the stray light) and imaged by the primary mirror M1.

With the solar simulator set at 0.5 AU, off-pointing acquisitions were performed as well, in order to understand whether Metis, by means of stray light analysis, can provide a feedback on the spacecraft pointing. The results are encouraging, and a preliminary method is proposed, even though it shall be revised for the flight phases.

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The design, development, implementation and test of Metis has been performed by an industrial consortium constituted by OHB Italia (acting as Prime Contractor towards ASI with the specific responsibility of System engineering, the optical subsystems, the electronics and the basic software) and Thales Alenia Space Italia (Co-Prime Contractor with the specific responsibility of the Telescope configuration and thermo-mechanical subsystems, the application software and the instrument AIT). ALTEC Company, as sub-contractor, provided logistic and technical support for the integration and calibration activity. The VLDA assembly was provided by MPS under Contract 2013-058-I.0 with the Italian Space Agency (ASI). The UVDA assembly was provided by MPS as German contribution to Metis thanks also to the financial support of DLR (grant 50 OT 1201). The primary and secondary mirrors were provided as Czech contribution to Metis; the mirror hardware development was possible thanks to the Czech PRODEX Programme.

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REFERENCES

- [1] Antonucci, A., Fineschi, S., Naletto, G., Romoli, M. et al., "Multi element telescope for imaging and spectroscopy (METIS) coronagraph for the Solar Orbiter," Proc. SPIE 8443, 844309.1-12 (2012).^[1]_{SEP}
- [2] Fineschi, S., Antonucci, E., Romoli, M., Bemporad, A., Capobianco, G., Crescenzo, G., Nicolini, G., Massone, G., Telloni, D., Focardi, M., Landini, F., Pancrazzi, M., Poletto, L., Pelizzo, M.-G., Da Deppo, V., Moses, J. D., Andretta, V., Naletto, G., Nicolosi, P., Spadaro, D., Berlicki, A., Uslenghi, M., Malvezzi, M., Teriaca, L., Abbo, L., Magli, E., "Novel space coronagraphs: METIS, a flexible optical design for multi-wavelength imaging and spectroscopy", Proc. SPIE 8862, 88620G (2013).
- [3] Romoli, M., Landini, F., Antonucci, E., Andretta, V., Berlicki, A., Fineschi, S., Moses, J. D., Naletto, G., Nicolosi, P., Nicolini, G., Spadaro, D., Teriaca, L., Baccani, C., Focardi, M., Pancrazzi, M., Pucci, S., Abbo, L., Bemporad, A., Capobianco, G., Massone, G., Telloni, D., Magli, E., Da Deppo, V., Frassetto, F., Pelizzo, M. G., Poletto, L., Uslenghi, M., Vives, S., Malvezzi, M., "METIS: the visible and UV coronagraph for solar orbiter", Proc. SPIE 10563, 105631M (2017).
- [4] Müller, D., Marsden, R.G., St. Cyr, O.C., Gilbert, H.R., The Solar Orbiter Team, "Solar Orbiter. Exploring the Sun–Heliosphere Connection", Sol. Ph., 285, 25–70 (2013).
- [5] Fineschi, S., Antonucci, E., S., Naletto, G., Romoli, M., Spadaro, D., Nicolini, G., Abbo, L., Andretta, V., Bemporad, A., Berlicki, A., Capobianco, G., Crescenzo, G., Da Deppo, V., Focardi, M., Landini, F., Massone, G., Malvezzi, M., Moses, J., Nicolosi, P., Pancrazzi, M., Pelizzo, M-G., Poletto, L., Schuhle, U., Solanki, S., Telloni, D., Teriaca, L., Uslenghi, M., "METIS: a novel coronagraph design for the Solar Orbiter mission", Proc. SPIE 8443, 84433H (2012).
- [6] Landini, F., Vives, S., Romoli, M., Venet, M., Romoli, M., Guillon, C., Fineschi, S., "External occulter laboratory demonstrator for the forthcoming formation flying coronagraphs", App. Opt. 50 (36), 6632-6644 (2011).
- [7] Romoli, M., and the Metis Consortium, "METIS Technical Specification", Tech. Rep. METIS-OATO-SPE-001, v.5.0 (2016).
- [8] Landini, F., Romoli, M., Capobianco, G., Vives, S., Fineschi, S., Massone, G., Loreggia, D., Turchi, E., Guillon, C., Escolle, C., Pancrazzi, M., and Focardi, M., "Improved stray light suppression performance for the solar orbiter/METIS inverted external occulter," Proc. SPIE 8862, 886204.1–19 (2013).
- [9] Bout, M., Lamy, P., Maucherat, A., Colin, C., and Llebaria, A., "Experimental study of external occulter for the Large Angle and Spectrometric Coronagraph 2: LASCO-C2," App. Opt. 39(22), 3955–3962 (2000).^[1]_{SEP}
- [10] Fineschi, S., Crescenzo, G., Massone, G., Capobianco, G. et al., "OPSys: optical payload systems facility for testing space coronagraphs," Proc. SPIE 8148, 81480W.1-10 (2011).
- [11] Tordi, M., Fineschi, S., Crescenzo, G., "The visible light source for METIS stray-light tests: preliminary design", Proc. SPIE 8862, 886210 (2013).