Challenges during Metis-Solar Orbiter commissioning phase

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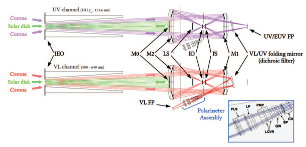
ABSTRACT

Metis is the visible light and UV light imaging coronagraph on board the ESA-NASA mission Solar Orbiter that has been launched February 10th, 2020, from Cape Canaveral. Scope of the mission is to study the Sun up close, taking high-resolution images of the Sun's poles for the first time, and understanding the Sun-Earth connection. Metis coronagraph will image the solar corona in the linearly polarized broadband visible radiation and in the UV HI Ly-α line from 1.6 to 3 solar radii when at Solar Orbiter perihelion, providing a diagnostics, with unprecedented temporal coverage and spatial resolution, of the structures and dynamics of the full corona. Solar Orbiter commissioning phase big challenge was Covid-19 social distancing phase that affected the way commissioning of a spacecraft and its payload is typically done. Metis coronagraph on-board Solar Orbiter had its additional challenges: to wake up and check the performance of the optical, electrical and thermal sub-systems, most of them unchecked since Metis delivery to spacecraft prime, Airbus, in May 2017. The roadmap to the fully commissioned coronagraph is here described throughout the steps from the software functional test, the switch on of the detectors of the two channels, UV and visible, to the optimization of the occulting system and the characterization of the instrumental stray light, one of the most challenging features in a coronagraph.

INTRODUCTION

Metis (Antonucci et al., 2020), the Solar Orbiter coronagraph, is designed to image the solar corona in an annular field of view centered on the Sun disk center and covering the range from 1.6 to 2.9 degrees. Metis is an externally occulted coronagraph with a novel inverted optical configuration (Fineschi et al., 2020), as shown in the figure, that takes images in the broadband linearly polarized visible light (580-640 nm) and, for the first time simultaneously over the entire field of view, in the narrowband HI Ly-α at 121.6 nm.



Solar Orbiter (Müller et al.) was launched on February 10, 2020, from Cape Canaveral, and went through the Near Earth Commissioning Phase (NECP).
During NECP, Metis coronagraph was switched on, functionally tested and characterized. In particular, the two mechanisms of the instrument, the one-shot sealing cap and the internal occulter positioning mechanism (IOM), were activated. All these activities were performed using a direct link with the spacecraft, sending commands and receiving telemetry in quasi real time, due to the light travel time from the ground station to the spacecraft and back.
NECP activity for Metis started on February 27 with the switch on and the short functional test to verify the operativeness of most of the instrument subsystems. The completion of Metis commissioning required 14 activity sessions that were completed on June 8, despite the covid-19 pandemic outbreak, with a few tests left and a bunch of features to be solved during the mission cruise phase. Nevertheless, these features do not block Metis science observations and the NECP was considered successfully completed.

THE IMPACT OF COVID-19 PANDEMIC ON METIS OPERATIONS

NECP for Metis was supposed to be carried on at the Solar Orbiter mission control center (MOC) at ESOC in Darmstadt, where the instrument team needed many representatives on site. Two or three from the team were allowed in a dedicated Solar Orbiter control room while the other representatives worked from a dedicated support area. Metis operations team would have been supported by a dedicated MOC engineer to coordinate the real time activity and the management of unexpected behaviors or anomalies to be solved within the session or reprogrammed.
The presence at ESOC has been possible only for the first two activities because the outbreak of the Covid-19 pandemic brought to a sudden stop the possibility to travel to ESOC. The Italian-German-Czech team behind the Metis coronograph was just getting ready to switch on the instrument for the first time, on February 27, when the decision was made that people from coronavirus hotspots in Italian regions, Piemonte and Lombardia, were no longer allowed to enter ESOC for safety reasons. For the second activity on March 6 only two representatives from a considered safe region of Italy were allowed in. Afterwords, a strict lockdown in both Germany and Italy forced to perform all the activities from home. The activity leaders were connected on one side via gmeet with the rest of the Metis team and via webex with MOC.
The situation became even more serious when several workers at ESOC tested positive for the virus, and the site effectively closed. The instruments were switched off on March 22 and NECP went on hold and it was not clear when the instruments could come back online. NECP was resumed about a week later. A skeleton staff returned and, with full social distancing measures in place, began working remotely with the instrument teams to get the commissioning done.
Security concerns required ingenious solutions such as viewing the ESOC control screens, which showed the data from the spacecraft, via a webcam. The main drawback of the 'home-office' set-up was the added delay between the action being performed by the spacecraft and the data about the status of the operation reaching the team. In addition to that, it was difficult to keep the instrument team in contact from home and running the link with ESOC without voice interferences.
The NECP ended with the first "virtual" ESA Mission Commissioning Results Review (MCRR) that declared NECP successful.

METIS COMMISSIONING ACTIVITIES

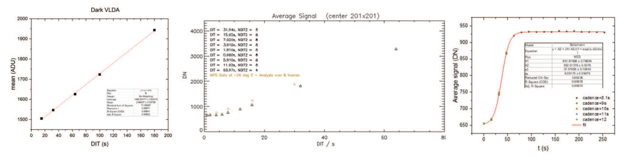
The Metis commissioning phase was planned to take place entirely in the NECP. The instrument was verified and tested on-ground during two short periods in December 2016 and in April 2017. The commissioning phase aims at verifying the electrical, mechanical, optical, thermal, and software functionalities of the instrument.
In order to maintain the demanding cleanliness requirements during the on-ground instrument testing, except when in vacuum, during the integration on the spacecraft and the full spacecraft activity till shortly before launch, Metis instrument was sealed by a protection cap. A Nitrogen purging flow was continuously provided to gently overpressurize the telescope cavity preventing the entrance of contaminants. After launch, the outgassing phase lasted about one month, a period during which the contamination/protection doors were held closed. An additional fast outgassing time (5 days) with the heat shield door closed was performed after the cap ejection.
The table lists all Metis NECP Each activity was performed in a few hours. All activities were successful with the exception of those highlighted in italics in the table.

Activity	Date	Activity description
IT-1	27/02/2020	Short functional test (SFT)
IT-2	06/03/2020	VL and UV dark images, Annealing heater test
IT-3	13/03/2020	Cap ejection: VL first light
IT-4#1	06/04/2020	*UV offset map upload*
IT-4#2	08/04/2020	UVD High voltage
IT-4#3	23/04/2020	UV first light and darks
IT-6A	11/05/2020	Stray light check with roll
IT-6B1	15/05/2020	Internal Occulter coarse alignment
RSC	28/05/2020	Coordinated campaign: Remote Sensing Co-alignment
IT-5	29/05/2020	Cosmic Ray algorithm, compression and radialization test
IIC	29/05/2020	Coordinated campaign: Inter-Instrument Communication
EMC	02/06/2020	Coordinated campaign: Electromagnetic Cleanliness
IT-6B2	03/06/2020	*Internal Occulter fine tuning*
IT-7	08/06/2020	Off-pointing stray light characterization and Polarimeter test

Throughout the full commissioning the thermal behaviour of the instrument was verified against the thermal model.
See details in the technical documents: Metis User Manual (METIS-ATI-MA-001) and the Metis Commissioning report (METIS-UNIFI-RPT-041 (available upon request).

MAIN COMMISSIONING: Detector Calibration Frames

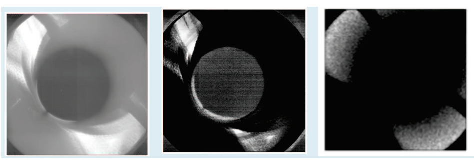
VL Dark and Bias
After the ejection of the Metis cap it is not anymore possible to acquire further dark images, because the heat shield door is not light tight. The dark map obtained during IT-2 will be used throughout the mission, with appropriate rescaling when necessary. The dark signal was acquired using increasing DITs. The average dark current is computed in a 512x512 pixels central box and their linear fit, with the fit parameters and their errors are also given (left plot).



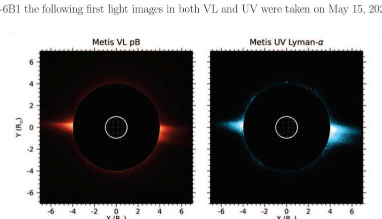
UV Dark and Bias
The dark signal has been measured at different exposure times (center plot). The stability in time has also been checked, and a transient effect (right plot) at the beginning of each acquisition, already noticed in the on-ground calibration of the instrument, has been studied. As tested during the ground calibration, the dark signal is independent on the voltage applied to the screen gap. Dark frames are being acquired as part of the in-flight calibration activities. A workaround to the transient issue has been adopted, while investigations are on-going

MAIN COMMISSIONING: IO Optimization and First Light

The first images in both channels show a slight misalignment of the occulting system. The occulting system consists of four components: the IEO, the disk light rejection mirror (M0), the internal occulter, IO, and the Lyot Stop. The IO is a circular stop that occults the light diffracted by the edge of the IEO, and the Lyot stop that blocks the light from the edge of M0, both imaged by the primary mirror. The Lyot stop, a circular occulter mounted in the back of M0, is less critical because it stops a secondary diffraction source.
The on-ground alignment verification showed a similar misalignment that was corrected. The second misalignment could be due to an impulse received by the IO during launch. These event confirm the importance of the presence of an IO mechanism to compensate for accidental misalignments during the integration and launch phases, especially for the most stray light sensitive visible channel.
The IO mechanism consists of two stepper motor actuators placed along crossed directions that support the IO. Each step actuation translates the IO by about 6 μm. The coarse alignment was carried out by performing a 10 step wide grid of positions for the two actuators and taking VL images for each position Comparison between IT-3 (left), on-ground calibration before IOM optimization (middle) and a Zemax OpticStudio© simulation with off-centered IOM (right).



After the IO optimization durint IT-6B1 the following first light images in both VL and UV were taken on May 15, 2020 from 0.63 AU.



MAIN COMMISSIONING: Stray light and Pointing

Stray Light Characterization
Given the large distance from the Sun, always above 0.5 AU, the Sun is very overocculted and we have stray light levels which are well below the required stray light rejection of 10^{-9} in mean disk brightness units.
We have to wait till the first perihelion of 2022 for an assessment of Metis stray light performance.
Two schemes have been used during commissioning. The first one involves a roll of the spacecraft around a sun-centered axis; the second one involves spacecraft off-pointings to bring the limb of the Sun close to the edge of the Sun disk rejection mirror.

Pointing Assessment
IStar observations within Metis FOV are very important to characterize and calibrate the instrument. In the VL channel, stars are commonly seen in the FOV and are often bright enough to stand out above the solar corona. Stars are also visible in the UV channel: they are typically early-type bright stars (type O and B) which emit conspicuously in the Metis UV narrow bandpass. Passes of this type of stars within Metis FOV are traced and represent a target of opportunity for Metis calibration.
Metis UV and VL reference frames: detectors' reference frames (black and red), instrument reference frame (blue), spacecraft reference frame (green), helioprojective cartesian reference frame (HPC) (yellow). For completeness, a Stonyhurst heliographic grid is also shown. Relative displacement and rotations between the various reference frames are amplified for better display clarity.

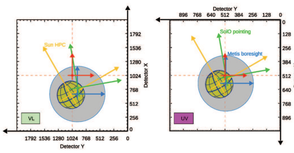


Table 2. Metis boresight and Sun center position during commissioning

	VL	UV
Sun center position (X_s, Y_s)	$(+25.6 \pm 0.6, -57.2 \pm 0.8)$ pixels $(+259 \pm 7, -580 \pm 9)$ arcsecs	$(+2.63 \pm 1, -4 \pm 1)$ pixels $(+54 \pm 38, -83 \pm 38)$ arcsecs*
Plate scale (S_X, S_Y)	10.138 ± 0.004 arcsecs/pixel	20.40 ± 0.06 arcsecs/pixel*
Residual angle $(\delta\rho)$	-0.08 ± 0.03 degrees	$+0.23 \pm 0.15$ degrees*
Pre-launch Metis boresight (X_b, Y_b)	$(+9.5, -59.5)$ pixels $(+96, -603)$ arcsecs	$(-8.5, -4.5)$ pixels $(-173, -92)$ arcsecs
In-flight Metis boresight (X_b, Y_b)	$(+23.5 \pm 1, -85.5 \pm 1)$ pixels $(+238 \pm 11, -867 \pm 11)$ arcsecs	$(1.6 \pm 2.5, -18.1 \pm 2.5)$ pixels $(+33 \pm 40, -370 \pm 401)$ arcsecs**

Acknowledgments and References

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See the proceedings paper for the detailed bibliography.

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