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Lunar Observations in Copernicus Sentinel-3: Implementing a new operation into a flying mission

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Abstract

The Copernicus Sentinel-3 satellites are a Polar Low-Earth Orbit constellation, jointly operated by EUMETSAT (routine operations) and ESA (Launch and Early Operations Phase, Commissioning and technology support) for the European Union Commission's Copernicus programme, with instruments designed for pointing (quasi) nadir during routine operations. Rotating the spacecraft "upside-down" to enable these instruments to point at the moon during satellite eclipse was not part of the original conceptualization of the Sentinel-3 system operations. The extreme temporal stability of the moon surface properties and the absence of atmosphere makes the moon a perfect calibration target for monitoring the radiometric stability of instruments in space. In the recent years, using the moon for post-launch performance assessment (in particular the radiometry) has been gaining momentum to enhance product quality in Earth Observation missions - especially given the stability required for monitoring climate change, and allowing to remove potential artefacts from the images such like stray-lights effects. However, designing and executing an activity that requires manoeuvring a spacecraft in a way that was not considered in the original design of the mission and platform requires strong cooperation in between the operators (EUMETSAT and ESA), the satellite prime contractor (TAS-F), and the instrument manufacturers, to ensure the success of the operation – keeping spacecraft safety as a priority. An outline of this co-operation and the constraints identified are presented. This paper presents the cooperative process and iterations to bring to life a new operation and the outcome of a successful campaign in 2022.

Keywords: Spacecraft Operations, Lunar calibration, Earth Observation, Spacecraft Instrument calibration, Space Mission Evolution

Acronyms/Abbreviations

AOCS	Attitude and Orbit Control System
CNES	Centre national d'études spatiales (National Centre for Space Studies)
EPS	EUMETSAT Polar System
ESA	European Space Agency
ESOC	European Space Operations Centre
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FDIR	Failure Detection Isolation and Recovery
FOV	Field of View
GIRO	GSICS Implementation of the ROLO model
GMS-5	Geostationary Meteorological Satellite - 5
GNSS	Global Navigation Satellite System
GSICS	Global Space-based Inter-Calibration System
IR	InfraRed

MHSTR	Multi-Head Star Tracker (S3 AOCS component)
MetOp	Meteorological Operational satellite
MODIS	Moderate Resolution Imaging Spectroradiometer (Terra / Aqua Instrument)
MWR	Micro Wave Radiometer (Sentinel-3 Instrument)
NPP	Suomi National Polarorbiting Partnership (satellite)
OLCI	Ocean Land and Color Instrument (Sentinel-3 Instrument)
ROLO	Robotic Lunar Observatory
RW	Reaction Wheel
S3	Sentinel-3
S3A	Sentinel-3A (satellite)
S3B	Sentinel-3B (satellite)
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor (SeaStar Instrument)
SEVIRI	Spinning Enhanced Visible and InfraRed Imager (Meteosat Second Generation Instrument)
SLSTR	Sea and Land Surface Temperature Radiometer (Sentinel-3 Instrument)
SRAL	SAR (Synthetic Aperture Radar) Radar Altimeter (Sentinel-3 Instrument)
SYN	Synergy (Sentinel-3 Product)
TAS-F	Thales Alenia Space France
USGS	United States Geological Survey
VIIRS	Visible Infrared Imager Radiometer Suite (NPP Instrument)
VIS	Visible

1. Introduction

The main driver to perform lunar calibrations on Copernicus Sentinel-3 (S3) satellites is to assess post-launch radiometric performance, dark offset modelling and stray light correction in the image processing for the Ocean and Land Colour Imager (OLCI) instrument. OLCI is a visible (VIS) and Near-IR instrument composed of five cameras with fixed field of view (FOV). In order to acquire the datasets to perform the calibrations, acquisitions of the Moon will be taken by rotating the spacecraft around its X axis and acquiring the Moon in the normal operational mode of the instrument.

A single observation was performed by the operations team at ESOC in July 2018, as part of the commissioning of Sentinel-3B, the second satellite of the constellation launched earlier that year [1]. After the success of this operation, the request to perform a single observation was extended to Sentinel-3A which was already in routine operations. Operation was updated by EUMETSAT with lessons learned and additional constraints with focus on mission availability were implemented. During 2022 a new Lunar Calibration campaign has been planned and executed in pursuance of an observation for each of the OLCI cameras in both of the Spacecraft in flight, totalling 10 observations. The purpose of the acquisitions was first to make an assessment of the stray-light correction algorithm for each camera, and to demonstrate the possibility of using OLCI lunar observations for radiometric performance assessment as an independent method to complement the nominal calibration strategy using a solar diffuser.

This paper reviews the background of the Sentinel-3 mission as part of Copernicus, and the role of the Lunar observations ensuring the long term sensor stability required for climate monitoring when they are implemented during the whole mission lifetime. An explanation of the designed operation and its constraints and trade-off is given, followed by an outline of the co-operative process required to first bring to life and then to routine operations the Lunar observations and the impact observed in operations due to the introduction of this operation.

2. Background

2.1 Copernicus Sentinel-3 mission

Copernicus is the European Union programme for monitoring the Earth's environment, it acquires in-situ and space observations. This programme aims to deliver long term operational data in a reliable and timely manner in order to enhance the management of the environment, mitigate the effects of climate change and strengthen civil security, and ensuring the availability of the necessary information to policy makers and public authorities. The programme is led by the European Union, with the support of ESA as a partner in the provision of the space component, EUMETSAT as a space segment operator and service provider, as well as the European Environmental Agency (EEA) and the European Center for Medium range Weather Forecast (ECMWF) and other European institutions contributing as core service providers. The Copernicus programme has six core thematic services dedicated to Atmosphere Monitoring, Marine Environment Monitoring, Land Monitoring, Climate Change, Security and Emergency Management [2].

The S3 mission is the result of a collaborative effort of the European Commission, ESA, EUMETSAT, French National Centre for Space Studies (CNES), industry providers and the data users. The satellites have been designed and built by a consortium of companies lead by Thales Alenia Space France. EUMETSAT and ESA worked together in the provision of the Ground Segment [3], coordination of operational products and the definition of the operational concept and share the responsibility to manage and operate jointly the mission. EUMETSAT is responsible of the processing of the marine and near real-time atmospheric products and the operation of the spacecraft in routine operations [4] while ESA processes the land and delayed-mode atmospheric products and operate the spacecraft from Launch and Early Operations Phase through the end of the Commissioning.

Sentinel-3 is part of the Copernicus Space Component and it is composed by a constellation of satellites that provide relevant space based data in support of the environmental monitoring of both land and ocean and contributing to ocean forecasting [5]. The constellation is currently composed by two flying satellites Sentinel-3A launched in 2016 and Sentinel-3B launched in 2018 currently flying 140 degrees of separation in a sun-synchronous orbit with Local Time Ascending Node (LTAN) 22:00 at an altitude of about 800 km. The provision of data will be ensured by the continuation of the constellation by the satellites Sentinel-3C and D [6].

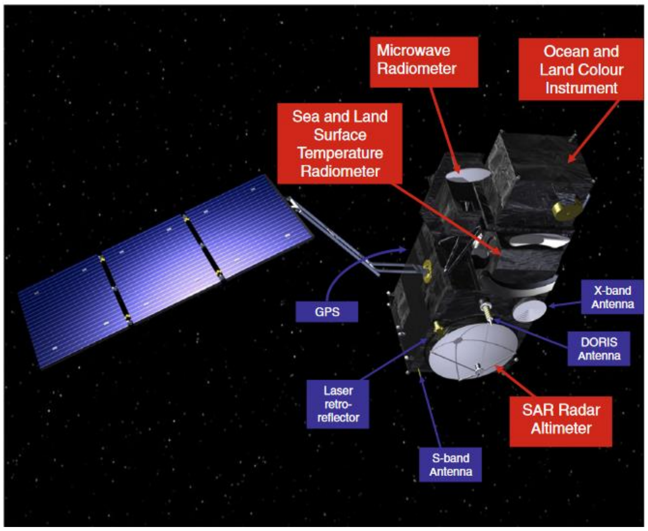

Fig. 1. Artist impression of a Sentinel-3 satellite and its main components [7]

The Sentinel-3 satellites and systems are design to fulfil two different primary missions [7]:

- Topography mission, aiming to provide sea surface topography, wave height and sea surface wind information. To address this requirements, the following instruments are flying:
  - SAR Altimeter Radar (SRAL): Ku-band (300 m after SAR processing) and C-band with a spatial resolution of approximately 300 m.
  - Micro Wave Radiometer (MWR), supporting SRAL for wet tropospheric correction, operating at dual frequency at 23.8 & 36.5 GHz.
  - A Precise Orbit Determination (POD) package including Global Navigation Satellite System (GNSS), DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) and a Laser Retro Reflector (LRR).
- Optical mission, to support the measurement of the sea surface temperature and global visible and short-wave infrared radiances measurement over oceanic, inland and coastal waters, land, sea-ice and ice-sheets. The following instruments address this mission:
  - Ocean and Land Color Instrument (OLCI), 21 spectral bands (400–1020 nm) with a swath width of 1270 km and a spatial resolution of 300 m. Acquisition is performed during the day part of the orbit, when angle in between the solar beams and its reflection to the spacecraft is less than 80 degrees.
  - Sea and Land Surface Radiometer (SLSTR), covering 9 spectral bands (550–12 000 nm), dual-view scan with swath widths of 1420 km (nadir) and 750 km (backwards), and a spatial resolution of 500 m. IR channels are active during the whole orbit while the VIS channels are not active during eclipse.

2.2 The use of the Moon as a calibration target in Earth Observation and Climate monitoring

Climate monitoring requires in orbit observational measurements to show consistency across the different sensing satellite instruments, both in the current missions and with a capability to extend it to future sensing satellite systems. In order to detect trends in the evolution of environmental parameters based on solar reflectance wavelengths, a very tight spacecraft instrument stability is required [8].

The Moon surface properties show an extreme temporal stability that makes it an ideal calibration target to monitor the radiometric performance of space-borne instruments in Earth Orbit [9][10]. The Moon seen from orbit constitutes a bright object against a dark and cold background, which allows as well to assess and adjust artefacts like stray-light effects during the image processing of Earth Observation products. In this way, the use of lunar observations is extending its use towards the final objective of improving the product quality of Earth observation product [11]. The use of the lunar observations in the calibration process relies on a photometric model of the Moon and, due to the complexity lunar surface, is compared with the integration of the acquired Moon signal to derive the lunar irradiance.

There is already extensive experience in the use of lunar observations for instrument calibrations coming back from the 1990s. The instrument designed to collect ocean biological information SeaWiFS on board of NASA’s SeaStar spacecraft performed monthly lunar observations [12]. Hundreds of scheduled and unscheduled lunar observations were performed by the MODIS instruments on board of Terra and Aqua satellites and used in cross-calibration exercises [13][14]. In the same way, approximately monthly acquisition of the Moon has been scheduled in VIIRS instrument on board of NPP [15]. The above mentioned are medium resolution Low Earth Orbit (LEO) platforms with an environmental monitoring objective, however this technique is used as well in high resolution satellites with civil and defence use, like in the case of PLEIADES [16]. The technique is used as well in Geostationary Earth Orbit (GEO) satellites like Japanese Meteorological Agency’s GMS5, United States National Oceanic and Atmospheric Organization’s GOES (10-15), Korean Meteorological Agency’s COMS, Indian Space Research Organization’s INSAT-3D or Chinese Meteorological Agency’s FY-2D/E/F [11][17].

2.3 Experience with Moon observations in EUMETSAT

The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) was founded in 1986 and is an operational organization to monitor weather, climate and the environment. Being an operational organization, it provides climate and weather data in a timely and reliable manner to help support in the monitoring of the oceans, land and atmosphere. Its satellite fleet and ground systems are designed and operated to provide products 24 hours a day, 365 days a year.

EUMETSAT facilities centralize the operations of both space and science ground segments. The cohabitation of different technical and scientific roles under the same organization facilitates interactions between interdisciplinary groups required to bring to life new operations and to disseminate knowledge of the benefits of new techniques among different teams and roles, expediting the necessary seek for compromise required in operations in between timely and complete data provision and system evolution. This ecosystem fosters the identification and introduction of new techniques beneficial for the scientific outcome of the mission.

Lunar calibrations are not new in EUMETSAT, they are part of the SEVIRI instrument calibration mounted in the Meteosat Second Generation (MSG) geostationary satellites and have been used during their commissioning and operational lifetime [18][19][20]. The first one of the satellites of a new generation of satellites, Meteosat Third Generation (MTG), has been launched in 2022. The Flexible Combined Imager (FCI) instrument will continue with the mission of SEVIRI and Moon calibrations are planned to be used to ensure the radiometric stability [21].

Moon observations are performed by the Eumetsat Polar System MetOp satellites taking advantage of the intrusion of the Moon during the deep space observations of the Microwave Humidity Sounder and are part as well of the acquisitions of GOME-2 (Global Ozone Monitoring Experiment-2) [22][23]. In coordination with CNES, dedicated lunar observations have also been performed by EUMETSAT with the IASI (Infrared atmospheric sounding interferometer) instrument to investigate the possibility to use the Moon for radiometric assessment in the thermal infrared [24].

EUMETSAT has been deeply involved in promoting sharing strategies in the Lunar calibration community and organized the first GSICS – CEOS/IVOS (Infrared and Visible Optical Sensors group / Committee on Earth Observation Satellites) lunar calibration workshop in 2014. During the workshop, the EUMETSAT implementation of the ROLO model, renamed GIRO (for GSICS Implementation of the ROLO model) was endorsed by the workshop participants to become the established publicly-available reference for lunar calibration, directly traceable to the USGS ROLO model. It was agreed that EUMETSAT will pursue the efforts to develop and maintain the

GIRO model in with collaboration of the USGS to ensure its traceability with the widely extended ROLO model [11].

2.4 Introduction of attitude manoeuvres into Earth Observation satellites

Moon observations can be acquired by space-born radiometers in various ways, depending on the mission and the engineering solutions implemented to support the mission requirements. For geostationary missions, the Moon crosses the instrument FOV when moving along its orbit. Specific acquisitions can also be performed by de-pointing the platforms [19][25]. For polar satellites, lunar measurements can be acquired through space ports when available, or thanks to platform manoeuvres along its orbit.

However, in the case of Sentinel-3, the instruments have a fixed FOV that does not extend beyond the Earth horizon, hence a rotation of the platform is required to capture the Moon. This situation is not a novelty, and it is shared with the technique performed by Terra/Aqua [13], that performs a roll in the night side of the orbit and NPP (Suomi National Polar orbiting Partnership satellite) that performs a roll manoeuvre during the day side of the orbit, resulting in a more constrained geometry to ensure spacecraft safety [14].

In recent years, EUMETSAT Flight Dynamics team and the EPS Flight Control Team have also performed an activity that has involved an extreme attitude manoeuvre and that has resemblances to the rotation of Sentinel-3 to observe the moon. As part of the MetOp-A satellite End of Life activities a “Back-Flip” has been performed in the spacecraft [26] for deep space acquisition before its successful deorbit in 2021.

3. Lunar observation operation definition in Sentinel-3

3.1 S3 AOCS overview

The Sentinel-3 spacecraft flies nominally in a nadir pointing mode (Zsc axis pointing towards Earth surface) with a yaw steering guidance that compensates the cross-track component of the relative velocity of the surface. Solar panel keeps rotating uniformly during the whole orbit. The AOCS is composed by a Multiple Head Star Tracker (MHSTR) with 3 optical heads, a GNSS system, Coarse Sun Sensors (CSS), two Magnetometers and two Coarse Rate Sensors (CRS). The available actuators are four Reaction Wheels, three Magnetorquers used for wheel off-loading in Nominal and Orbit Control modes, and a Reaction Control System with 2 sets of 4 thrusters that can provide thrust in +Xsc and –Xsc directions.

During Nominal mode, the attitude and angular rate are provided by the MHSTR and the position is given by the GNSS, while Coarse Rate Sensors are not included in the control loop.

3.2 Operation description

As it has previously outlined, the Moon observation manoeuvre has been defined as a rotation of less than 165 degrees around the X axis of the spacecraft to bring the Moon to the FOV of one of the five cameras of OLCI. This operation is performed during eclipse to reduce spacecraft risk, slews start and finish during the eclipse. The Dual Control Law and the FDIR configuration is modified during the slews covering the whole period while the spacecraft is pointing off-nadir and returning to normal before end of the Eclipse. Spacecraft yaw steering mode is stopped and guidance is Geodetic during the activity.

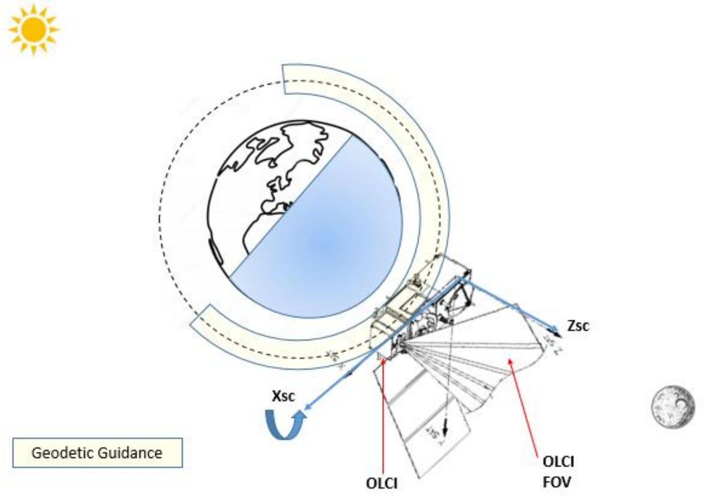

Fig. 2. Diagram of a Lunar observation

It is a precondition that the Moon has to be almost full, with a Moon Phase in between 6 and 8 degrees. This condition becomes necessary in the analysis, and subsequent selection, of calibration opportunities. The Moon Phase Angle is in general relevant in order to ensure the usability of the calibration data for stray-light analysis. It is defined as the angle cantered in the Moon in between the Sun and the Observer (see Fig. 3). A sign is typically attached as well to the moon phase value, indicating whether moon phase decreases (negative value; waning moon), or increases (positive value; waxing moon). This is relevant as a different sign means a different part of the moon visible (different reflectance).

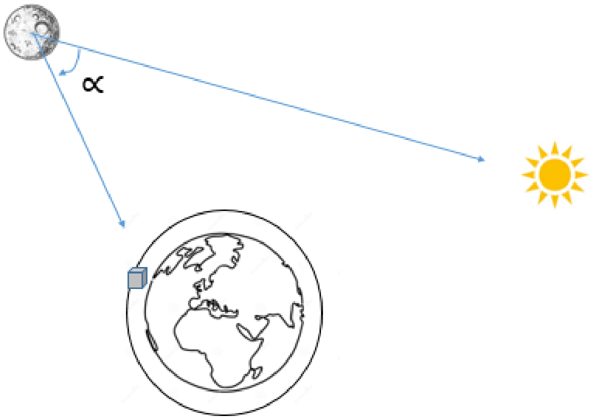

Fig. 3. Moon Phase Angle definition

OLCI nominal mode of data acquisition and SLSTR day science packets are activated during 5 minutes centred around the Moon observation in order to ensure the data acquisition. The Lunar observation time off-pointing can be used to obtain benefits for instruments other than OLCI taking advantage of the Moon or deep space observation.

3.3 Operational constraints

As indicated before, the analysis performed by the TAS-F brought the following geometrical constraints and platform constraints:

- Rotation is performed around the X axis; for the first test, the Z axis would point to the middle of the moon observation (for later observations, different positions/cameras are made pointing to the moon, by changing the magnitude of the roll rotation, while still respecting all constraints).
- Rotation is to be below 165 degrees while the spacecraft is in Nominal AOCS mode with Geocentric Guidance mode, as otherwise all star tracker heads would get pointing too close to the Earth (limb). This guidance mode will be maintained during 3030 seconds.
- The activity is performed with 4 Reaction Wheels; an event action is implemented to abort the operation in case a reaction wheel is lost.
- Slew starts 69 seconds after the umbra crossing (for allowing prior commanding/preparation prior to start slew and while already in eclipse), slews last 600 seconds with a tranquilization period, ensuring in this way the completion of the operation inside the eclipse.
- MHSTR shall be healthy. Dual Control Law is adjusted and some AOCS on-board surveillances (FDIR Level 2) are modified.
- GNSS configuration is modified to take into consideration the reduced visibility over the navigation constellation when spacecraft is rotated.
- GNSS is to be taken out of the AOCS loop and invalidated to avoid the spurious release of Orbit Position tele-commands.
- Nominal pointing is to be available before the start of the next X-Band pass (before entering in visibility of the mission data downlink station).
- All data will be downloaded without the need to extend the X-Band passes (nominal station to be used).

Scientific and operational requirements set by Remote Sensing and Flight Control Teams:

- Simultaneous outages of S3A and S3B will be avoided and the Moon calibration will be avoided if the altimetry mission of the other satellite is in outage.
- Any planned spacecraft and instrument events, like calibrations, decontaminations, etc. have priority.
- The Moon Phase Angle will have to be as consistent as possible and with the same angle (positive or negative) for all observations. Note first observation in 2018 had a Moon Phase Angle of -6.46 (constraint ± 2 degrees maximum with a goal ≤ ± 1 degrees).
- Achieve Moon view at nadir and with sufficient time margins:
    - across-track: OLCI nadir (s/c Z axis) view corresponds to camera 4, the centre of the image is required or at least as far as feasible away from camera edges.
    - along-track: acquisition with large time margins is required to ensure that all potential stray-light effects are contained in the image, i.e. considering that the Moon covers about 9 sec observations, the minimum 2xMoon sizes are required at each side
- Avoid performing the manoeuvre during times the spacecraft overflies one of the transponder sites in Crete or Svalbard (relevant for Altimetry Mission)
- Possibility to enable all SLSTR channels and perform deep space calibration for channels S8 and S9 with dedicated Front End Electronics gain settings (whenever the SLSTR scientific teams request it).

4. Co-operative process: from conceptualization to routine operations

This section presents a chronology of coordination activities leading to the successful introduction of this new operation and the trade-off process to create new technical and operational requirements leading to a successful and safe inclusion of a regular lunar observation operation in all the satellites of the Sentinel-3 constellation.

The possibility of performing a Lunar observation during the Commissioning campaign of S3B appears at first in February 2018 as an outcome of the Flight Acceptance Review (FAR) with the objective to ensure the stray-light requirements were met. TAS-F was tasked to deliver a series of technical notes covering a study on the potential manoeuvre definition and its verification, together with studies of the impact in the AOCS, Power Subsystem, Thermal Control System, SRAL/MWR and FDIR.

The outcome of the feasibility studies concluded with the overall design outlined in the previous section, including the maximum rotation to ensure that at least one Optical Head is not blinded by the Earth, the possibility to perform safely the slews completely in eclipse, a trade-off in between performing it with or without Yaw steering mode and the need to modify the AOCS Level 2 FDIR and GNSS configuration. Communications in between TAS-F and ESA resulted in an analysis on the necessity to test the Lunar observation on the Virtual Engineering Model, resulting as a conclusion that it would not provide additional representability and would be equivalent to test on the spacecraft simulator in ESOC, being it enough for the verification stage and the future validation of the calculated manoeuvre. Operation was executed twice by ESOC, the first one with testing purposes without the Moon in the FOV of the instrument and finally performing the first Lunar calibration on July 2018.

After the successful execution of the single Moon observation of S3B during the commissioning, the OLCI-SYN Quality Working Group, comprising ESA, EUMETSAT, Mission Performance Centre (MPC) and community experts, extended in November 2019 the recommendation to perform a single observation with S3A. Flight Control Procedure was reviewed and improved after the first execution, including the new constraints to remove the GNSS from the AOCS loop during the manoeuvre. The safety constraints on the spacecraft that were comprehensively defined during the commissioning phase were complemented with new operational constraints by EUMETSAT with a focus in mission availability, The result was a single observation performed by S3A in July 2020.

The recommendation of the OLCI-SYN QWG Quality Working Group and the involved parts was extended to perform a new series of calibrations covering all the cameras (5 in each satellite), with 2 month intervals interleaved between S3A and S3B. EUMETSAT provided schedules and calibrations opportunities to the Joint Steering Group for their study in November 2020.

In June 2021, EUMETSAT and ESA tasked TAS-F to perform an assessment on the safety of performing the Moon calibrations. After a successful outcome, the Copernicus Joint Steering Group and the S3 Joint Operations Board recognized the positive income and agreed in October 2021 to perform a longer campaign that took place from January to October 2022.

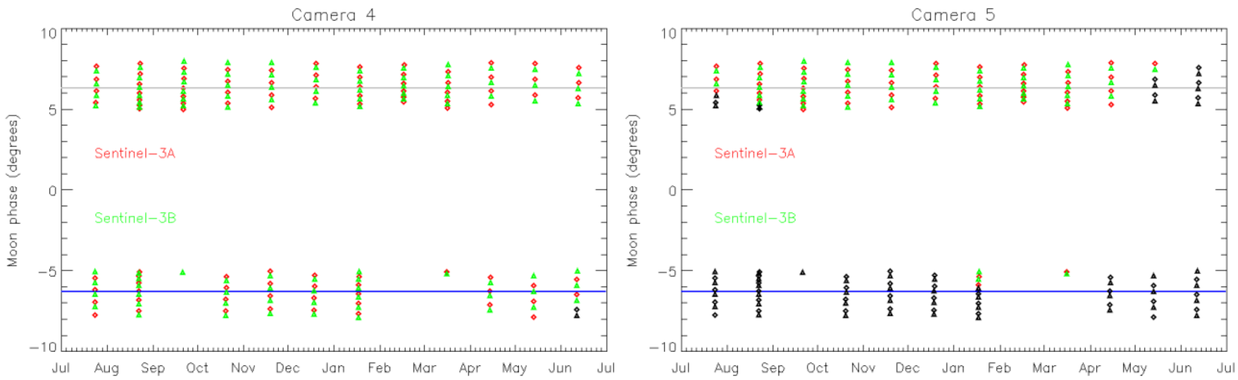

Fig. 4. Study of the availability of calibration opportunities in 2022 for S3A/S3B OLCI camera 4 and 5. Both negative and positive phases, similar to the 2018 case, are considered. Black dots are non-admissible opportunities.

The original two Lunar observations had been performed for Camera 4 using a negative Moon Phase Angle. However, the roll angle needed for observing the Moon limited the number of opportunities for negative phases in particular for Camera 5, as illustrated by Fig. 4.. The EUMETSAT Remote Sensing and Products and Flight Operations teams agreed to acquire the Moon with positive Phase Angle, a decision that will affect all the future observations, leading to a dataset built using positive Moon Phase Angle observations. A potential relaxation of the constraints on the distance of the Moon to the edges of the image would increase the number of potential calibration opportunities and has been under debate.

During the OPS board of October 2022, the recommendation to continue performing lunar observations with a 2-month frequency was extended for a campaign covering from November 2022 to December 2023. All the observations of this campaign will use the Nadir pointing camera (cam. 4).

5. Impact of the introduction of the new operation

5.1 Mission Outage

Sentinel-3 has two primary missions: An Optical Mission, consisting of OLCI and SLSTR, and the Altimetry Mission composed of SRAL, MWR and the positioning systems on-board. The outage in OLCI is minimized given that the operation is performed in eclipse. However, this is not the case for the rest of the instruments, making it necessary to look for synergies with the needs of the rest of the instruments. Each of the manoeuvres makes the spacecraft point off-nadir for around 30 minutes and to navigate without Yaw steering mode for around 50 minutes.

OLCI data will be available but degraded since the moment the spacecraft enters into the conventional day to the moment the guidance mode is recovered. SLSTR IR channels will be impacted from the moment the guidance mode changes to Geocentric guidance to the moment the Yaw steering mode is recovered, however the VIS channels will only be impacted from the end of the eclipse until the recovery of the nominal steering mode.

Regarding the altimetry mission, SRAL data is typically degraded during the time in between the start of the forward slew to the end of the backward slew. However, MWR is impacted all the period the spacecraft guidance mode is not nominal. And despite the availability of raw data, the outage affecting the products could be wider because of how the higher level products are impacted by the outages.

Table 1. Outage for each instrument in each Lunar observation during the 2022 campaign

Observation Number	**2**	**3**	**4**	**5**	**6**	**Average**
S3A	**Outage [mm:ss]**					**[mm:ss]**
	Jan-22	Mar-22	May-22	Jul-22	Sep-22	
OLCI	06:23	06:17	05:01	08:51	09:12	07:09
SLSTR IR	50:30	50:30	50:30	50:30	50:30	50:30
SLSTR VIS	19:08	18:43	17:52	17:14	17:57	18:11
SRAL	29:38	29:21	30:00	31:20	31:20	30:20
MWR	50:30	50:30	50:30	50:30	50:30	50:30
DORIS	50:30	50:30	50:30	50:30	50:30	50:30
S3B						
	Feb-22	Apr-22	Jun-22	Aug-22	Oct-22	
OLCI	09:54	05:01	08:48	05:58	06:58	07:20
SLSTR IR	50:30	50:30	50:30	50:30	50:30	50:30
SLSTR VIS	19:24	17:52	17:10	17:47	17:51	18:01
SRAL	29:21	30:56	31:20	30:58	30:53	30:42
MWR	50:30	50:30	50:30	50:30	50:30	50:30
DORIS	50:30	50:30	50:30	50:30	50:30	50:30

If the outage introduced by the Lunar observations is analysed comparatively with the rest of on-board routine activities that create outages, we can observe it is small in comparison with others. During 2022, the ratio of outage of the moon calibration with respect to other routine activities has been of a 7.2% for S3A and 7.3% for S3B. The result of the comparison with the total outage is that the Lunar observations were a 3.7% for S3A and a 3.4% for S3B of the total outage.

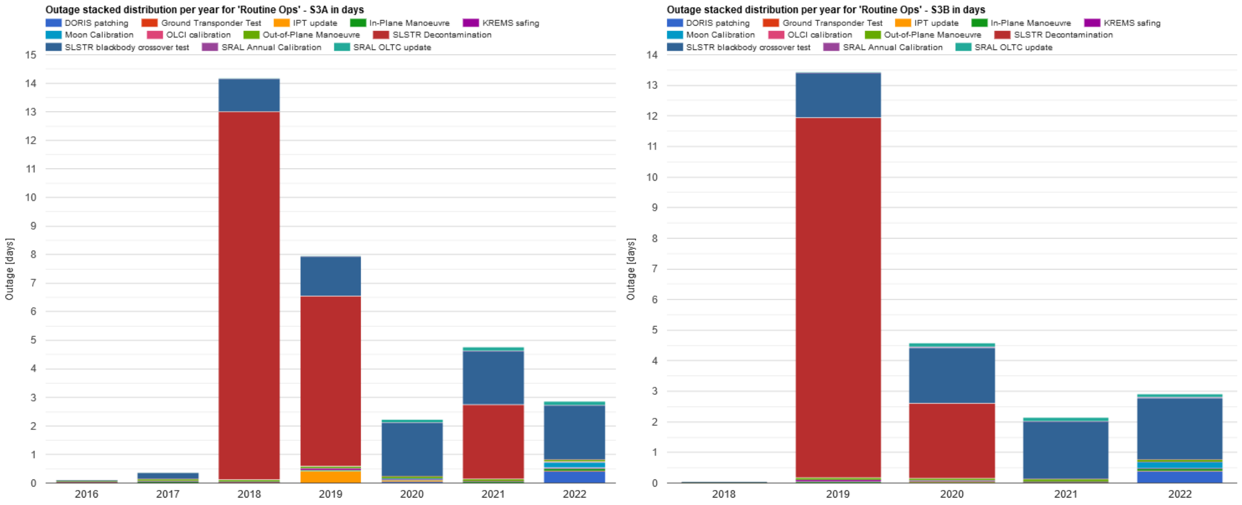

Fig. 5. Moon calibration outage in comparison with other routine expected outages

5.2 Impact on Spacecraft

The observed behaviour in the spacecraft during the operation have been in the expected ranges. No big impact has been observed in any subsystem. In Table 2 it is possible to observe how relevant AOCS parameters are within limits in comparison with the thresholds that would trigger an FDIR reaction during the operation.

Table 2. Ratio of the absolute maxima value during the operation with respect to the FDIR limits during the 2022 Moon calibration campaign

S3A	**Lunar Obs. #**	**2**	**3**	**4**	**5**	**6**	FDIR Limit
S/C Angle rate	**X**	51.43%	45.71%	48.57%	48.57%	45.71%	0.0175 rad/s
	Y	18.18%	18.18%	21.82%	21.82%	18.18%	0.0055 rad/s
	Z	3.92%	3.92%	5.88%	6.67%	7.84%	0.0255 rad/s
RW Speed	**1**	18.46%	18.46%	16.15%	16.15%	18.08%	260 rad/s
	2	33.85%	33.85%	25.38%	13.85%	33.08%	
	3	37.69%	36.54%	25.77%	16.15%	38.08%	
	4	20.77%	18.85%	17.31%	15.38%	18.46%	
RW Friction	**1**	5.33%	14.67%	12.00%	12.00%	14.67%	0.15 Nm
	2	21.33%	9.33%	6.67%	5.33%	10.00%	
	3	26.67%	12.00%	6.67%	6.67%	13.33%	
	4	13.33%	11.33%	11.33%	10.67%	11.33%	
Camera		**5**	**1**	**2**	**3**	**4**	
S3B							
S/C Angle rate	**X**	45.71%	48.57%	49.14%	51.43%	45.71%	0.0175 rad/s
	Y	18.18%	25.45%	20.00%	18.18%	18.18%	0.0055 rad/s
	Z	7.84%	5.10%	5.88%	7.84%	7.84%	0.0255 rad/s
RW Speed	**1**	18.08%	38.27%	39.07%	40.38%	42.31%	260 rad/s
	2	33.85%	33.85%	33.23%	32.69%	38.46%	
	3	37.69%	35.85%	36.65%	37.31%	31.54%	
	4	20.77%	35.85%	35.24%	35.38%	35.00%	
RW Friction	**1**	6.00%	8.00%	8.67%	8.67%	10.67%	0.15 Nm
	2	21.33%	21.33%	20.67%	20.00%	21.33%	
	3	26.67%	24.67%	26.00%	26.67%	26.67%	
	4	13.33%	18.00%	21.33%	18.00%	16.00%	
Camera		**5**	**1**	**2**	**3**	**4**	

Some Thermal impact can be observed as a transient effect during the operation itself. Temperature increase are within limits. Special attention may be necessary when it affects the instruments, however the impact is confined to the time order of magnitude in which the data is degraded.

The temperature increase affecting OLCI can be observed as an example in the plot in Fig. 6 that has been inserted for reference showing the temperatures over the year 2022 of the S3A OLCI electronics. The increase, in the order of 1 deg.C returns to nominal after some orbits.

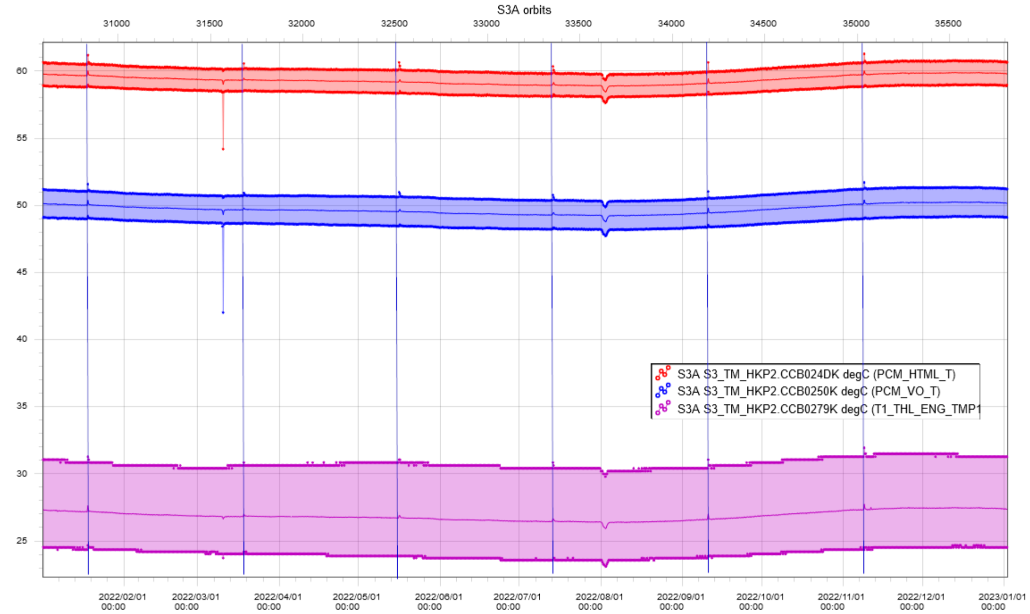

Fig. 6. S3A OLCI Electronic Unit temperatures during 2022, vertical lines indicate the presence of a Lunar observation

It is possible to observe temporary temperature increases in SLSTR, as an example the temperature of the electronics of one of the channels has been plotted in context and during a Lunar observation and it is possible how temperature increases temporarily. SLSTR is a cryogenic instrument and it is possible to observe peaks in the temperature of the compressor and displacer during these operations.

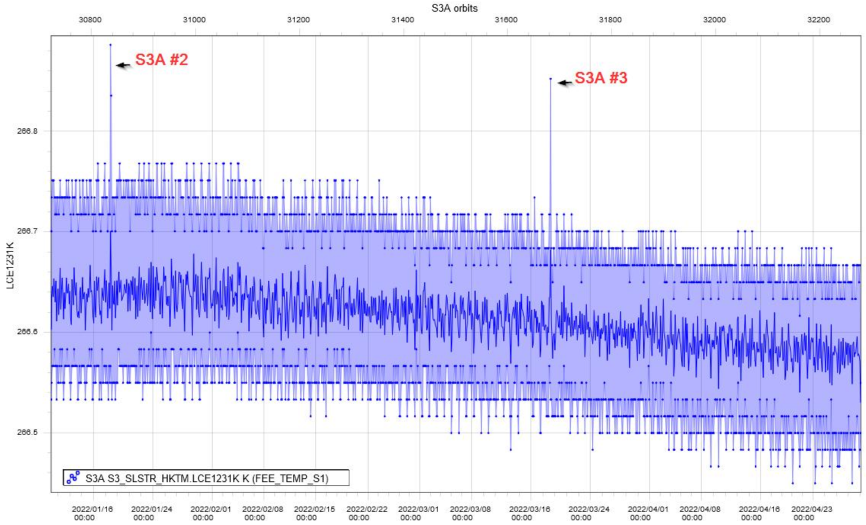

Fig. 7. Temperature of the SLSTR Front End Electronics Channel 1 during the Q1 2022 where two Lunar observations can be observed in context

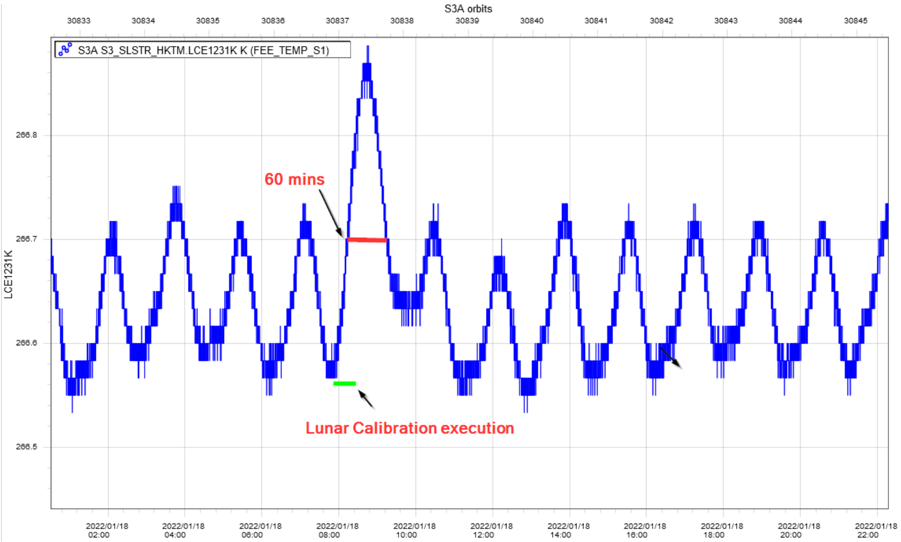

Fig. 8. Close-up view of the SLSTR Front End Electronics Channel 1 Temperature during Lunar calibration #1 in January 2022

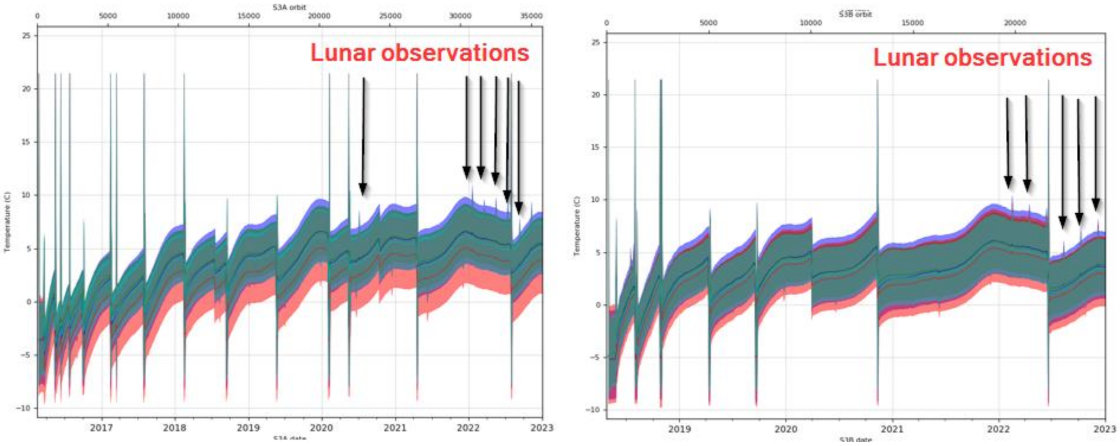

Fig. 9. SLSTR cryogenic system compressor and displacer temperatures shows peaks during Lunar calibrations (S3A left, S3B right)

6. Conclusion

The introduction of Lunar observations in Sentinel-3 showcases how cooperation in between the involved parts of a space mission can evolve the capabilities of the mission and how improvement of products is a continuous process through the whole lifetime of a mission.

Implementing a new operation is a good example of the need for compromise in space missions. New operational concepts can be introduced without compromising the safety of a flying spacecraft. However, an operation driven by one of the instruments on board of a platform introduces outages in other instruments, and this can be used as an opportunity to look for synergies and take advantage of the operation.

The processing and analysis of the images obtained during the campaign performed in 2022 will help assess the performances of the OLCI stray-light correction algorithm and its analysis will open the door to demonstrate the possibility of using OLCI lunar observations for radiometric performance assessment. Following the recommendation of the OLCI-SYN Quality Working Group (QWG), a new observation campaign is ongoing during 2023, paving the way to introduce this operation as part of the routine activities of the Sentinel-3 constellation and its continuation in the future satellites Sentinel-3C and D.

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