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# Results of capturing the Moon with Copernicus Sentinel-2

**Pablo Rodríguez Llorca[a*], Muhammad Shoaib Malik[b], Jamie Salt[c], Andrea Ferrari[d], Franco Marchese[e]**

[a] *Copernicus Sentinel-2 Spacecraft Operations Engineer, Telespazio Germany GmbH, Europaplatz 5, 64293 Darmstadt, Germany, pablo.rodriguez.llorca@telespazio.de*
[b] *Copernicus Sentinel-2 Spacecraft Operations Engineer, Telespazio Germany GmbH, Europaplatz 5, 64293 Darmstadt, Germany, m.shoaib.malik@telespazio.de*
[c] *Copernicus Sentinel-2 Spacecraft Operations Engineer, ESA-European Space Operations Centre, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany, jamie.salt@esa.int*
[d] *Copernicus Sentinel-2 Operations Manager, ESA-European Space Operations Centre, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany, andrea.ferrari@esa.int*
[e] *Head of Copernicus Sentinels Optical Imaging. Missions Operations Unit, ESA-European Space Operations Centre, Robert-Bosch-Straße 5, 64293 Darmstadt, Germany, franco.marchese@esa.int*
* Corresponding Author

## Abstract

The Moon is an attractive instrument calibration target for satellites because it is not affected by atmospheric effects and can be acquired directly, i.e. without a Sun diffuser. For the Copernicus Sentinel-2C and D missions, Moon calibrations will in future augment the different calibrations performed in routine in the A and B models, and thereby improve instrument performance comparisons over time and between spacecraft. This is especially valuable for a long-term mission such as Copernicus Sentinel-2, whose imaging products are frequently used in combination with those of other Earth Observation missions (e.g., Landsat, Copernicus Sentinel-1/3). The Copernicus Sentinel-2 payload is a push-broom imager, meaning that the spacecraft is nominally nadir-pointing. Put simply, to acquire a Moon image, the spacecraft will slew up to -130 deg. roll angle during eclipse and capture the target crossing over one of its detectors.

The particular challenge for Copernicus Sentinel-2 is that the system requirement was only introduced for the C and D models (launch foreseen in mid-2028), while the A and B spacecraft (launched in 2015 and 2017 respectively) were already in their routine mission phase. This means both spacecraft and the ground segment were not initially foreseen to perform this complex operation. So, the overall objective was to introduce this manoeuvre without impacting the design. The simplicity and robustness of the concept is of vital importance, as the successful operation of the Copernicus Sentinel-2 mission relies on seamless interaction and collaboration between ESA sites, i.e., the Flight Operations Segment, located at ESOC (Darmstadt, Germany) and the Payload Data Ground Segment, located in ESRIN (Frascati, Italy).

This article describes the operational concept, the in-orbit validation (as part of the in-orbit-commissioning phase) and the implementation of the Copernicus Sentinel-2C Moon Calibration into the periodic routine activities.

**Keywords:** Earth observation, Multi Spectral Instrument, Moon, Calibration, Copernicus, Sentinel-2

## Acronyms/Abbreviations

Assembly, Integration and Testing (AIT)
Acquisition and Orbit Control System (AOCS)
Electrical and Power System (EPS)
European Space Agency (ESA)
European Space Operations Centre (ESOC)
European Space Research Institute (ESRIN)
European Space Research and Technology Centre (ESTEC)
Extended Fine Pointing (EFP)
Field of view (FOV)
Flight Control Team (FCT)
Flight Dynamics Team (FDT)
Flight Operations Segment (FOS)

Generic File Transfer System (GFTS)
Ground Segment Validation (GSV)
Gyro Stellar Estimator (GSE)
In-Orbit Commissioning (IOC)
Inertial Measurement Unit (IMU)
Mass Memory and Formatting Unit (MMFU)
Mission Performance Centre (MPC)
Moon Calibration Opportunity Report based on operational orbit (MOCAR-O)
Moon Calibration Opportunity Report based on reference orbit (MOCAR-R)
Multi Spectral Instrument (MSI)
Nominal Fine Pointing (NOM-FP)
Nominal Payload Planning File (NPPF)
Optical Communication Payload (OCP)
Orbital position (OPS)
Payload Data Ground Segment (PDGS)
Post Launch Support Office (PLSO)
Planned Moon Calibration Report (PMCR)
Sun/Moon/Earth to Star Tracker Boresight Report (SUMO)
Tailored Parameter File (TPF)

## 1. Introduction

The Copernicus Sentinel-2 constellation consists of two Earth observation satellites that use a Multi Spectral Instrument (MSI) operating from the visible to shortwave infrared spectral range to address land and emergency user services. The instrument is a fixed push-broom imager that is Nadir pointing in nominal spacecraft attitude [1]. With Copernicus Sentinel-2B and -2C currently in routine operations in space, and Copernicus Sentinel-2A providing an extended service supporting the two other satellites, Copernicus Sentinel-2D has by now completed the Assembly, Integration and Testing (AIT) activities. It is currently in storage and its launch is expected in the year 2028. The onboard software and hardware of all four spacecraft models is widely identical, with only minor differences in the GPS/GNSS receiver modules. The satellites are controlled and operated from the European Space Operations Centre (ESOC) of the European Space Agency (ESA) located in Germany. The spacecraft operations carried out from ESOC are mainly monitoring, orbit maintenance and collision avoidance, subsystems maintenance, mission planning and operations definition. The requests for the utilisation of the payload are provided by the European Space Research Institute (ESRIN), of the European Space Agency (ESA), located in Italy. The purpose of this centre is to perform the payload planning, delivery of the input requests to the Flight Operations Segment (FOS), user services interface, quality control (calibration, validation, quality monitoring and instrument performance assessment) and processing and archiving the acquired images.

The exposure of the satellite to the space environment produces a continuous degradation of optical surfaces that impacts the performance of the MSI. For this reason, the instrument is calibrated regularly to ensure that the requested performance level is reached and that instrument performance comparisons over time and between spacecraft can be done. This is especially valuable since the Copernicus Sentinel-2 products can be used in combination with those of other Earth observation missions (e.g. Landsat, Copernicus Sentinel-1, Copernicus Sentinel-3).

The nominal calibrations foreseen for Copernicus Sentinel-2A and -2B are either impacted by atmospheric effects or cannot be acquired directly because they require the motion of the MSI's Calibration and Shutter Mechanism (CSM). Such calibration operations are [2]:

- Dark signal calibration: MSI images a dark target during eclipse, performed every two weeks
- Absolute radiometric calibration: the CSM is moved to a position that allows the Sun illuminating the instrument's diffuser, performed once a month
- Vicarious calibration: perform acquisitions over selected sites with known properties, e.g. the Saharan desert, performed every day

Imaging the Moon does not require to move the CSM and is not affected by the Earth's atmosphere, but only needs to slew the spacecraft and point the MSI directly towards the target. The benefit of using the Moon at a given phase to calibrate the instrument is that constant illumination characteristics are ensured and, therefore, every calibration can be performed under the same lighting conditions. The new concept will augment the calibration operations and improve the instrument's product quality. However, the operation has been conceived for Copernicus Sentinel-2C and -2D but was not originally designed for Copernicus Sentinel-2A and -2B. Moreover, the operational implementation had to consider its routine application on multiple spacecraft while ensuring a comparable illumination (i.e. Moon phase), which was the major driver for the design of the operational flow. On top of that, a major constraint was to introduce the new operation without changing the satellite design.

The activity has been designed for Copernicus Sentinel-2C and -2D, but considering the possibility to extend it to the previous models. It is not common to implement new operational concepts into a flying constellation, and typically the operation needs to be analysed, designed, tested on ground, tested in space during the in-orbit commissioning (IOC) phase and, finally, implemented as a routine operation. Copernicus Sentinel-2C was launched in September 2024 and the Moon calibration operation validated in orbit during the IOC. Ever since the satellite was launched, two Moon acquisitions have been made.

The risks that could jeopardize the flying satellites are related to the large slew that is required to point the MSI towards the Moon and the automated actions that can be triggered on the spacecraft to keep it safe if different conditions are met:

- Pointing the MSI towards the Moon requires a slew of up to -130° around the roll axis.
- The high power demand of a slew around the roll axis could trigger the Failure Detection, Isolation and Recovery (FDIR) actions which might cause undesired reconfigurations of the satellite subsystems and, thus, aborting the calibration operation. Bearing in mind that the solar array is pointing away from the Sun, it is desirable to avoid any kind of reconfiguration during a non-nominal orientation of the spacecraft.

In the following sections a description of the operational concept and the results after the execution on Copernicus Sentinel-2C are shown.

## 2. Operational concept definition

In short, the Moon needs to cross the MSI field of view while the images are being taken. In order to achieve this, the spacecraft needs to roll to point the MSI towards the target. To support this activity, different dedicated products have been implemented and tailored by the Ground Segment:

- Moon Calibration Opportunity Report based on the reference orbit (MOCAR-R), which includes all the future calibration opportunities, which fulfil the platform constraints, based on a long-term prediction of the orbit
- Moon Calibration Opportunity Report based on the operational orbit (MOCAR-O), which is an equivalent to the MOCAR-R but using the results of the orbit determination process and its future prediction, instead of the reference orbit.
- Task Parameter File (TPF), which contains the command sequences, input parameters and relevant timings for the platform commanding.
- Nominal Payload Planning File (NPPF), which is the mission planning input file and contains all the payload operation requests.
- Sun/Moon/Earth to Star Tracker Boresight Report (SUMO), including the possible star trackers blinding caused by either the Sun, the Moon or the Earth. The Copernicus Sentinel-2 star trackers are robust against Moon blindings.
- Planned Moon Calibration Report (PMCR), which includes information about the slew manoeuvre (e.g. slewed angle, slew start and end time, etc).

The nature of this operation requires the coordinated interaction between three different teams:

- the Payload Data Ground Segment (PDGS) team, which performs a trade-off between calibration opportunities predicted in the MOCAR-R and the impact on the nominal acquisition and downlink scenario. Once an opportunity is selected, the PDGS team thereafter includes a dedicated request in the NPPF that regularly produces and delivers to the spacecraft operators.
- the FOS Flight Dynamics Team (FDT):
    - computes the calibration opportunities and creates the MOCAR-R and MOCAR-O, the MOCAR-R is then sent to PDGS.
    - using the MOCAR-O, computes the details of the manoeuvre to slew the spacecraft and sends it to the FCT in the TPF

  - monitors the correct performance of the spacecraft platform AOCS activities and units.
- the FOS Flight Control Team (FCT):
  - processes the NPPF file and generates the mission planning stacks of commands.
  - processes the TPF file and builds the stack of commands to perform the manoeuvre.
  - uplinks both mission planning and manoeuvre commanding
  - offline system monitoring of the platform and payload status including the correct execution of the activity: In case of anomalous system behaviour, the FCT performs troubleshooting and recovery activities with the support of the Post Launch Support Office (PLSO) and Industry teams.

The cycle of events can be seen in Figure 1.

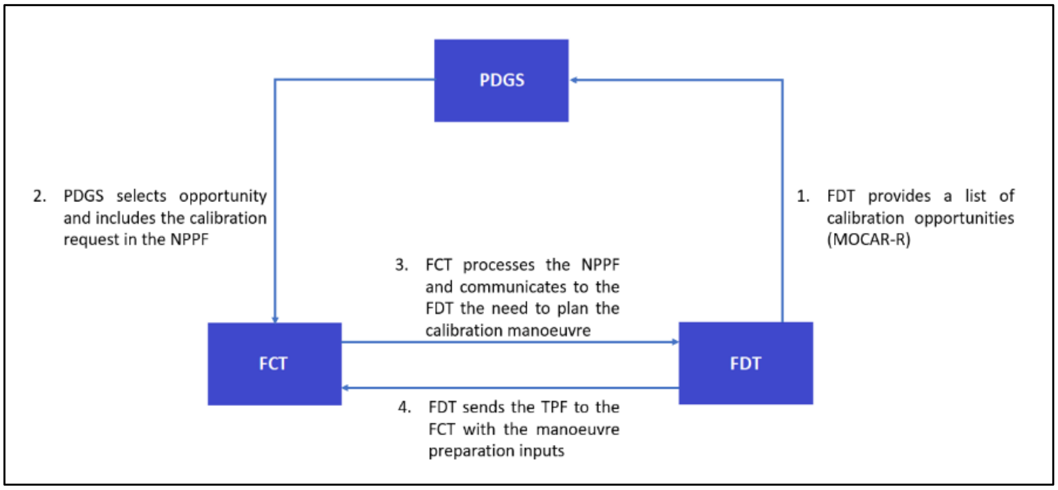

*Figure 1. Cycle of events in the MSI Moon observation.*

Figure 1 shows that the process starts by FDT generating the MOCAR-R and distributing. Then, PDGS chooses a calibration opportunity and includes the request in the NPPF. Once this file is received by the FCT, it is processed and the payload activities are planned. When a request for the Moon calibration is detected in the NPPF, the FDT generates a TPF based in the MOCAR-O, which is used by the FCT to create the platform's stack of commands.

The preparation of the activity needs to be divided into two parts -payload and platform activities- because PDGS requests are mostly based on geometric considerations using long-term predictions included in the MOCAR-R, while the platform activities make use of a short-term fine-tuning originating from the most recent orbit determination and included in the MOCAR-O.

More details about the definition of the operational concept can be consulted in [3].

### *2.1. Detection of calibration opportunity and payload activities*

As a first step, PDGS selects a calibration opportunity from the MOCAR-R that is generated by the FDT based on the following criteria:

- A Moon imaging shall be done monthly
- The Moon's phase angle must be between 7° and 55°
- The Moon is, at that moment, crossing the field of view (FOV) of a single MSI central detector
- The operation must be done in eclipse, to avoid any impact on other subsystems or the MSI imaging availability

Once selected, PDGS includes the request in the NPPF that is delivered every second week to the FCT. Upon NPPF processing, the FCT will identify the Moon calibration request and will simultaneously plan and uplink the payload activities, and coordinate with the FDT the generation of a TPF with the parameters to plan the platform activities.

These consist of the battery boost charging and the slew of the spacecraft to point to the Moon. The slew is part of the platform activities and will be further described in section 2.2.

It is understood that critical operations will have priority and will abort the MSI calibration in case of otherwise simultaneous execution (e.g. a collision avoidance manoeuvre).

The PDGS request in the NPPF adds an OPS tagged sequence of commands that was defined in a procedure [4] to enable or disable specific telemetry packets, perform the subsequent MSI mode transitions, start and stop recording instrument data into the Mass Memory and Formatting Unit (MMFU).

### 2.2. *Platform activities*

The satellite will slew a maximum of -130° around the roll axis to point the MSI's line of sight towards the Moon. The slew is limited to avoid both the star trackers being blinded by the Earth and any impact on the MSI radiators. At the end of each slew, a tranquillisation time is reserved to allow the spacecraft attitude to stabilise and ensure pointing accuracy during the observation. Such tranquillisation is also considered after the back-slew and before any MSI nominal data takes are resumed.

The sequence of events and AOCS sub-modes transitions before and after a calibration opportunity, as well as its start-, mid- and endpoint, can be seen in Figure 2.

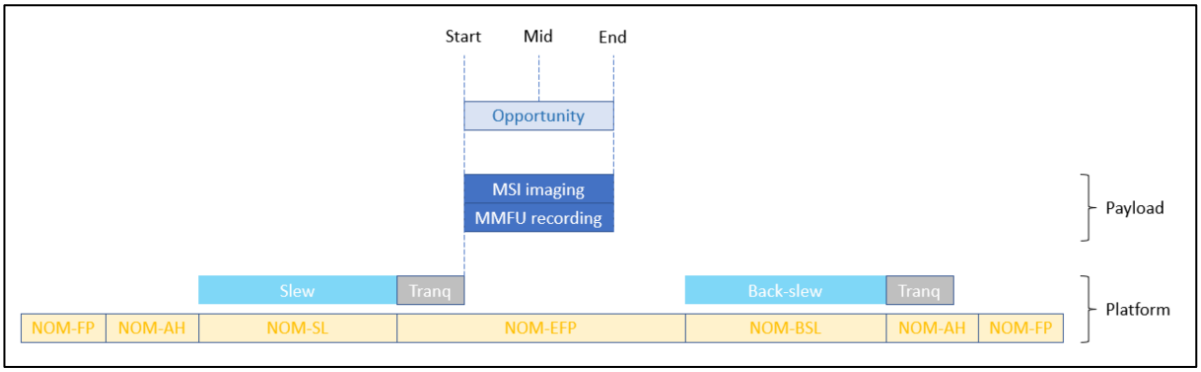

*Figure 2. Platform sequence of events and AOCS sub-modes transitions.*

Nominally, the AOCS mode used in operations is the Normal mode (NOM). It is further divided in six sub-modes, each having different pointing accuracy control thresholds. When violated, the attitude control systems are triggered to counteract. The NOM sub-modes are defined as follows [5]:

- Normal Acquisition (NOM-ACQ): it is used when entering NOM from a different AOCS mode, and it ensures that the attitude is stable enough for NOM.
- Normal Fine Pointing (NOM-FP): spacecraft is nominal pointing with high pointing accuracy (normal nadir pointing as payload is imaging in this mode).
- Normal Attitude Hold (NOM-AH): spacecraft is nominal pointing with moderate pointing accuracy.
- Normal Slew (NOM-SL): the spacecraft initiates the slew towards a target orientation.
- Normal Extended Fine Pointing (NOM-EFP): the spacecraft maintains a given attitude (other than normal nadir pointing) with high pointing accuracy (equal to NOM-FP)
- Normal Back Slew (NOM-BSL): the spacecraft initiates the slew towards the nominal pointing.

The NOM-FP and NOM-EFP sub-modes feature the lowest attitude errors to ensure a good pointing while the MSI is imaging. The main difference between them is that NOM-EFP is not pointing with the nominal attitude. All these sub-modes use the same hardware configuration.

The slew and back-slew have a duration that depends on the spacecraft roll angle. The EFP phase duration is constant and set to the maximum allowed by the spacecraft, with a duration of 265 s. The duration of the tranquilisation phase is set to 180 s, which is the result of an analysis on the attitude errors that in the worst-case scenario can take up to 180 s to drop back to acceptable values.

### 2.3. *Coordination of Platform and Payload Activities*

Since the payload and platform operations need to be precisely synchronised, the timing and duration of the different activities are predefined.

The payload's activities, as shown also in Figure 2, must start once the tranquilisation phase after the slew is completed [6]. The transition from the SL to the EFP sub mode is automated and must be planned in advance. As reference, the start time of the imaging opportunity plus the duration of the tranquilisation phase can be used.

Additionally, another waiting period after the last transition back to NOM-FP and before the uptake of subsequent nominal MSI data takes is needed: it has been observed on Copernicus Sentinel-2A and -2B that the convergence of the Gyro Stellar Estimator (GSE), which is used on-ground by PDGS for image and geolocation processing, is impacted after a transition from an invalid to a valid GPS/GNSS navigation solution. Consequently, the image processing is affected until the GSE fully converges. An analysis of the time to converge in the worst-case scenario showed that the separation must be 897 s. Only then, the nominal science imaging can be continued. Figure 3 shows an outline of the events after a calibration opportunity, where the GSE starts converging at the end of the back-slew. The MSI should start imaging only once the convergence has been reached, to avoid any impact on the quality of the acquisition. The end of the eclipse phase is also included, as no data takes are foreseen to occur until the spacecraft is over an illuminated area.

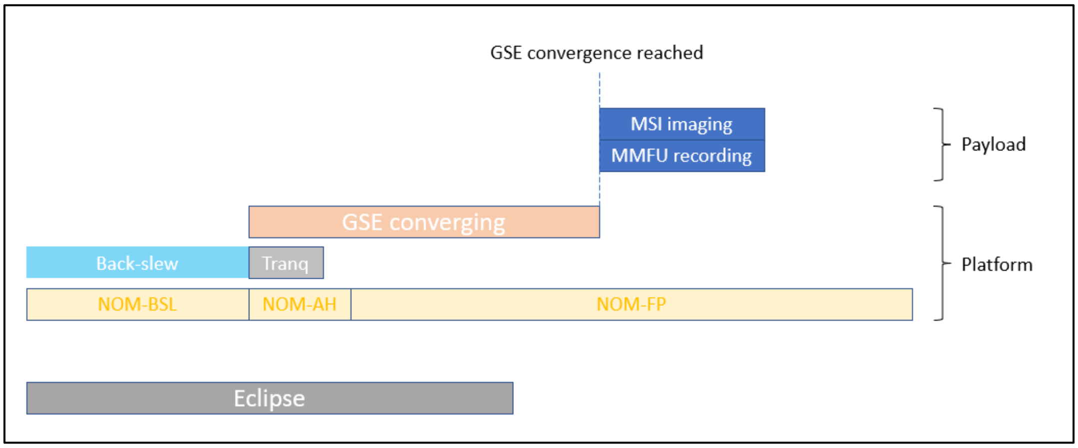

*Figure 3. GSE convergence waiting period prior to MSI observation.*

During eclipse, the solar array of the satellite cannot provide any power, therefore the power source during the calibration operations is the onboard batteries. However, both the slew and MSI activities will cause an additional power demand. Therefore, the battery end-of-charge voltage (EOCV) needs to be increased in advance to perform boost charging. The EOCV needs to be increased from 32 V up to 32.6 V one orbit before the start of the slew, and will be set back to its nominal values after the spacecraft status has been checked after the operation and during the following nominal S-band contact with the ground stations. The exact value of the EOCV increase is the result of an analysis performed by the spacecraft manufacturer.

To correct for the aberration that is introduced in the data takes by the rotating Earth during observations, the Copernicus Sentinel-2 satellites have a controlled motion around the yaw axis, called yaw steering. It is zero at the poles and maximum when crossing the ascending and descending nodes. This way, the yaw steering reference frame of the spacecraft has a misalignment of 0° at the poles and ±4° when flying over the Equator. This controlled motion needs to be disabled before starting the slew and must be re-enabled after the back-slew.

To ensure the synchronisation of the payload and platform activities, three reference times have been defined and are shown in Figure 4. For the payload, **P0** is the midpoint of the calibration interval, which is based on the MOCAR-R. Based on the payload's time reference **P0**, the first platform time reference **T0** can be established to determine the start of the slew before the MSI imaging. This reference will be used to plan the start of the increase of the batteries voltage one orbit before the slew time, which is necessary to avoid running into an undervoltage. Therefore, the difference between **P0** and **T0** must be equal to the duration of the slew, plus the tranquilisation phase, plus half of the opportunity duration [7].

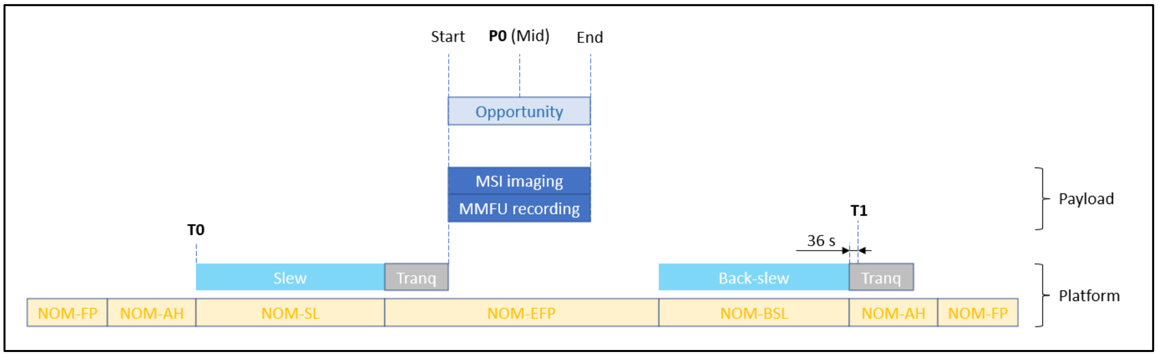

*Figure 4. Reference times to plan the platform and payload activities.*

The second platform time reference **T1** is the moment at which the yaw steering is re-enabled after the back-slew, thus allowing to return to the nominal mode NOM-FP. **T1** is computed from **T0** adding the slew, the NOM-EFP phase, the back-slew and 36 s. This extra gap is the time needed to reach a stable attitude after the back-slew that allows enabling the yaw steering. Since the enabling of the yaw steering temporarily distorts the attitude errors, the transition to NOM-FP will be scheduled two minutes after **T1**, to allow the attitude errors to stabilise. This is then considered the end of the overall activity.

## 3. Execution and results

The first Moon calibration opportunity after the Copernicus Sentinel-2C launch occurred on September 20th, 2024. As part of the IOC activities, the activity was planned as described above to finally validate the operation while keeping a special attention not only to the successful synchronisation of both the payload and platform activities (i.e. the correct and stable pointing while the MSI is acquiring the image of the Moon) but also to the motion dynamics. The target spacecraft orientation had to be correctly reached and the attitude and rate errors dumped in the expected time, to ensure a proper stability during the MSI observation. This is a key aspect, as a slew around the roll axis had never been tested in space for angles greater than 28°. Although not expected to occur, the off pointing of the GNSS receivers could lead to a loss of tracked satellites and a degradation of the navigation solution, so a special attention was also placed on some of the GNSS receiver parameters.

The requested Moon calibration required a -123.75° slew. The rotation around the roll axis and the AOCS sub-mode transitions are shown in Figure 5 in the blue and red respectively (note that the AOCS mode is also plot in green, but it does not change and remains in NOM-FP).

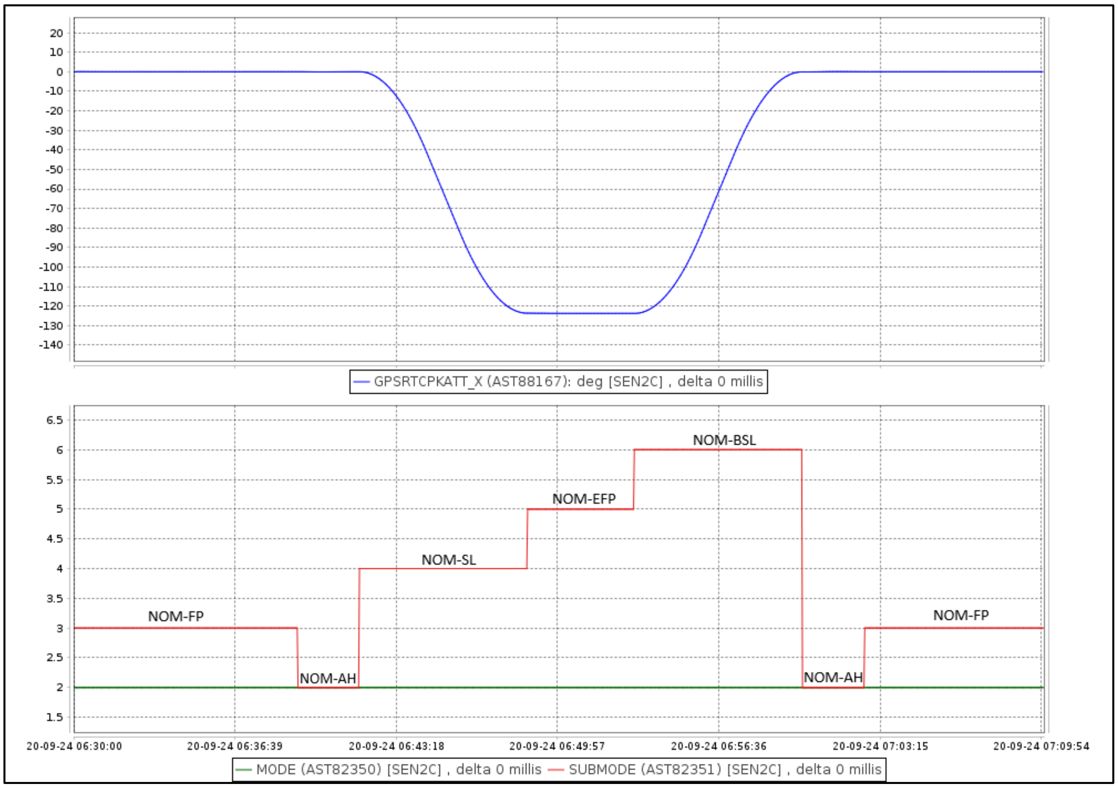

*Figure 5. Roll slew and AOCS mode transitions*

*In the previous image, the the description of each AOCS submode is shown*

Figure 5 shows that the mode transition were executed successfully and at the expected times, which validates the prediction of the automatic sub-mode transitions, which depend, amongst other parameters, on the stability of the spacecraft after the slew. Moreover, the measured slewed angle was stable at -123.760°, which shows an off-pointing of 0.012° with respect to the commanded rotation. This difference had no impact on the image acquisition and it is within the attitude error limits and requirements for the EFP sub-mode.

One of the most important aspects of this special operation is the synchronisation between the platform and the payload activities. The spacecraft needs to slew to the right pointing and maintain that attitude while the MSI is acquiring the Moon. All this needs to occur when the target is in the field of view of the instrument, which is predicted based on a geometrical analysis that takes into account the position of the Moon with respect to the satellite's orbit. The successful synchronisation of platform and payload activities is shown in Figure 6:

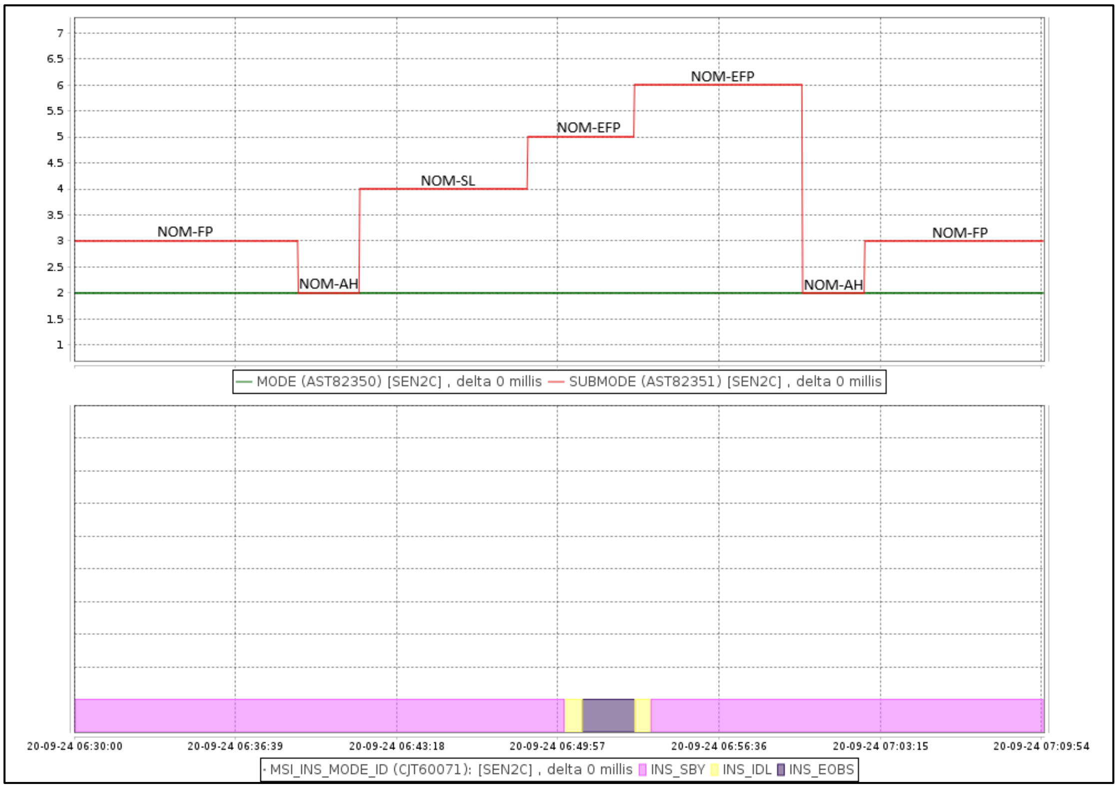

*Figure 6. AOCS mode vs MSI mode.*

The previous image shows how the MSI changes from Standby mode (*INS_SBY*), to an Idle mode (*INS*_IDL) and ultimately to Observation mode (*INS_EOBS*) when the AOCS mode is NOM-EFP. Here it can be seen how the observation does not start upon transition to NOM-EFP because there is a tranquillisation phase at the end of the slew before starting the MSI imaging.

The attitude errors can be seen in Figure 7, where two spikes are shown right after transitioning to the AOCS mode NOM-AH, and that are caused by the disabling and later enabling of the autonomous yaw steering. When it is disabled, the spacecraft changes the control reference frame and rapidly corrects the attitude to reach a near-zero off-pointing. Upon enabling it, it rotates to reach the correct yaw off-pointing that is needed for the spacecraft's position on its orbit.

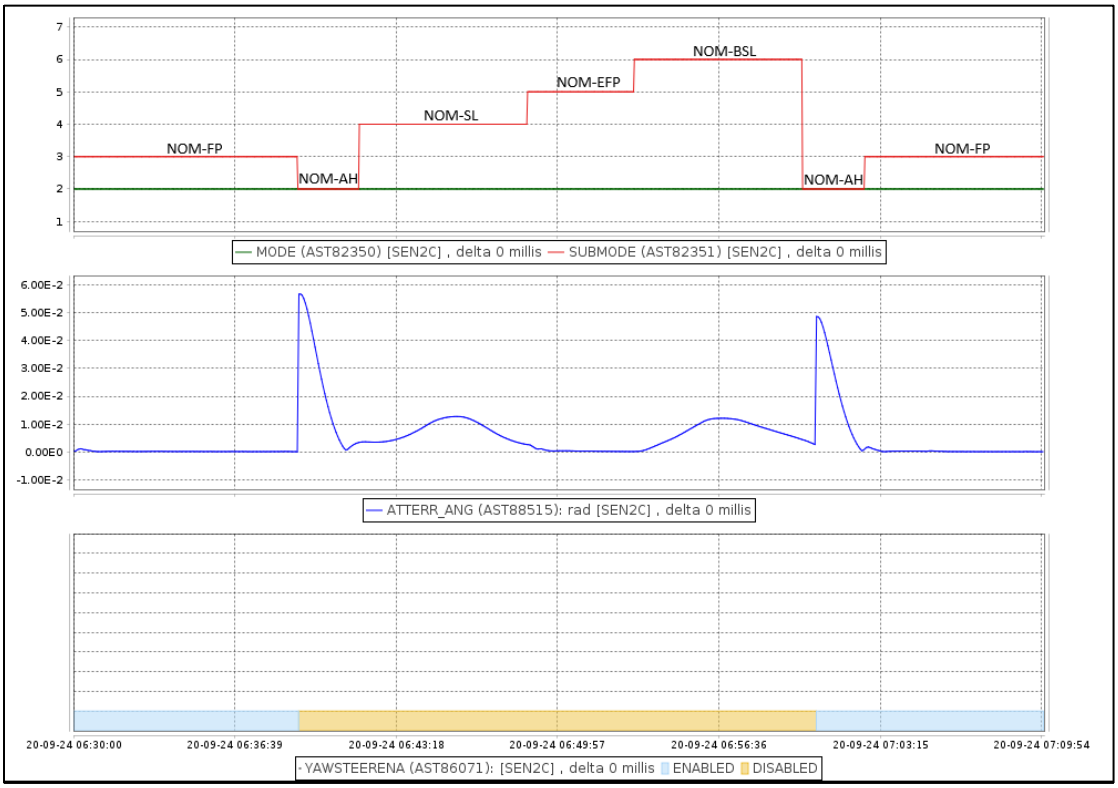

*Figure 7. Attitude error during the operation.*

During the slew phase the maximum attitude error was 0.0127 rad and the satellite reached a maximum of 0.0121 rad during the back-slew. On the other hand, at the start of the NOM-EFP phase the maximum attitude error was 0.0026 rad, which decreased rapidly below the required 400 µrad for this AOCS sub-mode. One of the risks of this operation is that the satellite could take long to drop the attitude error within. If it stays more than 180 s over the value 0.0012 rad it will abruptly reconfigure the spacecraft to the NOM-ACQ mode, which implies truncating the operation and slewing the satellite back to the nominal pointing. With this first Moon calibration, it was confirmed that the satellite reacted as expected and took only 20 s to decrease the attitude error below the upper limit.

Figure 8 shows the impact of the satellite’s off-pointing in the GNSS receiver’s navigation solution. While the solution remained valid throughout the operation, it is noticeable how the geometrical dilution of precision increases to a local maximum coinciding with the spacecraft pointing at the Moon and, thus, away from the nominal pointing of the GNSS antennas. Although this can be explained by the simultaneous decrease in the number of GPS/Galileo satellites being in the field of view and tracked, similar observations have been made during the nominal operation of the spacecraft. As predicted, there can be an impact but the unit is able to continue operating safely.

*Figure 8. Geometrical dilution of precision of the GNSS receiver.*

The data acquired during the operation was later post-processed and the final result can be seen in Figure 9 [8].

*Figure 9. Moon's image taken from Copernicus Sentinel-2C [8]*

## 4. Conclusions

The use of the Moon as a calibration target for the Copernicus Sentinel-2C MSI is a new operational concept whose definition, implementation and execution spanned through several years. All the details, including the results of the first calibration have been described in this document.

The fact that the activity was only requested for the Copernicus Sentinel-2C and -2D models, and not for the two predecessors, implied as a main constraint for the operation to avoid a change in the satellite's design. On top of this one, other limitations were defined, such as the need to perform the activity in eclipse, to minimise risks on the payload and the impact on the nominal science acquisition, or the requirement to target a Moon phase of 30°.

Both the process to define the operation and the one to execute it implied a coordination and interaction between several teams that are located in different European countries. The definition implied splitting the operation in two parts -payload and platform activities- that needed to be synchronised to ensure a correct and stable pointing of the MSI while the image of the Moon was being acquired. The process had been validated on ground during the Ground Segment Validation Tests against a simulator, and it was successfully executed in space during the first Moon calibration that was executed on September 20th 2024. Ever since, two other Moon calibrations have been performed with similar results.

The driver of the definition of the Moon calibration activity was to add the satellite-level operation into the S2 operational concept in a safe but streamlined way, so it may be routinely performed on multiple S/C with the existing level of support. Although it has not been considered for Copernicus Sentinel-2A and -2B, the operation has been defined taking into account that it could be adopted by these two satellites in the future. Copernicus Sentinel-2C started the routine Moon calibrations on March 25th 2025.

## Acknowledgements

The definition of the operation to calibrate the Copernicus Sentinel-2 instrument by direct observation of the Moon is the result of a close interaction between different teams. We would like to thank the Project and PLSO teams in ESTEC, PDGS, Airbus Defence and Space GmbH, the mission manager and the FOS-FDT for their support.

## Disclaimer

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