17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023.

SpaceOps-2023, ID # 449

Capturing the Moon with Copernicus Sentinel-2

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Abstract

For Earth Observation missions performing optical imaging, the Moon poses an attractive target for instrument calibration because it can be acquired directly, i.e., without the use of a Sun diffuser or atmospheric effects. For the Copernicus Sentinel-2 mission, Moon calibrations will in future augment the monthly Sun calibrations 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, Sentinel-1/3). The Copernicus Sentinel-2 payload is a multispectral push-broom imager in a fixed, nadir-pointing position with the spacecraft in a nominal attitude. Therefore, to acquire an image of the Moon, the whole spacecraft will need to slew up to a roll angle of -130°and capture the target crossing over one of its detectors during eclipse.

A particular challenge for Copernicus Sentinel-2 is that the system requirement was only introduced for the C and D models (with launch dates foreseen in 2024 and 2026 respectively), while the A and B spacecraft (launched in 2015 and 2017 respectively) are already in their routine mission phase. This means both flying spacecraft and the ground segment were not initially foreseen to perform this complex operation. Therefore, the overall objective is to introduce this new activity without impacting the existing design.

This article describes the major achievement in designing a Moon Calibration operations concept that will allow the operation to be performed safely and routinely, while maximising on-ground automation and minimising changes to the existing ground segment systems. The simplicity and robustness of the concept is of vital importance, as the successful operation of the Copernicus Sentinel-2 mission relies on the 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).

Copernicus Sentinel-2C will pioneer the approach during its in-orbit-commissioning phase, which will enable a subsequent application to the other flying Copernicus Sentinel-2 spacecraft without jeopardising the science return. The spacecraft commanding was recently validated successfully during an on-ground system test with the flight model, shortly before it was put into storage awaiting launch. The next milestone is testing the end-to-end FOS-PDGS interaction, foreseen during the upcoming Ground Segment Validation campaign.

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 Phase (IOCP)
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. With Sentinel-2A and -2B currently in routine operations in space, Sentinel-2C and -2D have by now completed their Assembly, Integration and Testing (AIT) activities. They are currently in storage and their launch is expected in the years 2024 and 2026, respectively. 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, Sentinel-1, Sentinel-3).

In the current operational scheme for Sentinel-2A and -2B three types of nominal calibration operations are performed on a regular basis:

- Dark signal calibration: MSI images a dark target during eclipse, performed every two weeks
- Absolute radiometric calibration: the MSI's Calibration and Shutter Mechanism (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

These calibration operations either cannot be acquired directly (in the absolute radiometric calibration the CSM movement is required) or are impacted by atmospheric effects. Imaging the Moon is not affected by the Earth's atmosphere and does not require the need to move the CSM, but only to point the MSI directly towards the target by slewing the spacecraft itself. Using the Moon at a given phase to calibrate the instrument ensures constant illumination characteristics and, therefore, every calibration will 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 Sentinel-2C and -2D but was not originally designed for 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.

Even though the activity has not been requested for Sentinel-2A and -2B, it has been designed considering the possibility to extend it to the flying satellites. 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 phase (IOCP) and, finally, implemented as a routine operation. Introducing an activity on a flying spacecraft without prior on-ground testing requires it to be validated to ensure the safety of the mission. The entire activity will be validated end-to-end during the Sentinel-2C IOCP to characterise and optimise the operation and ensure that the satellite's behaviour follows the predictions. Given the similarities of Sentinel-2C with the two flying spacecraft, the activity may be theoretically implemented also on Sentinel-2A and -2B even though the on-ground testing was not performed on them.

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. So far, the slew around the yaw axis was tested on ground and in space on Sentinel-2A and -2B, when validating or executing orbit maintenance and collision avoidance manoeuvre operations, and only roll slews of up to 15° were tested during the in-orbit commissioning phase.
- 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 detailed description of the operational concept, mainly its design and implementation, future validation, and implementation on Sentinel-2.

2. Operational concept definition

In short, the spacecraft needs to slew around the roll axis to point the MSI towards the Moon. Once in the new pointing configuration, the MSI can image the Moon. In order to support this activity, the following dedicated products will be 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.
- Tailored Parameters 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 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, two of them belonging to the FOS:

- the Payload Data Ground Segment (PDGS) team, which performs a trade-off between calibration opportunities presented 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 S/C 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.

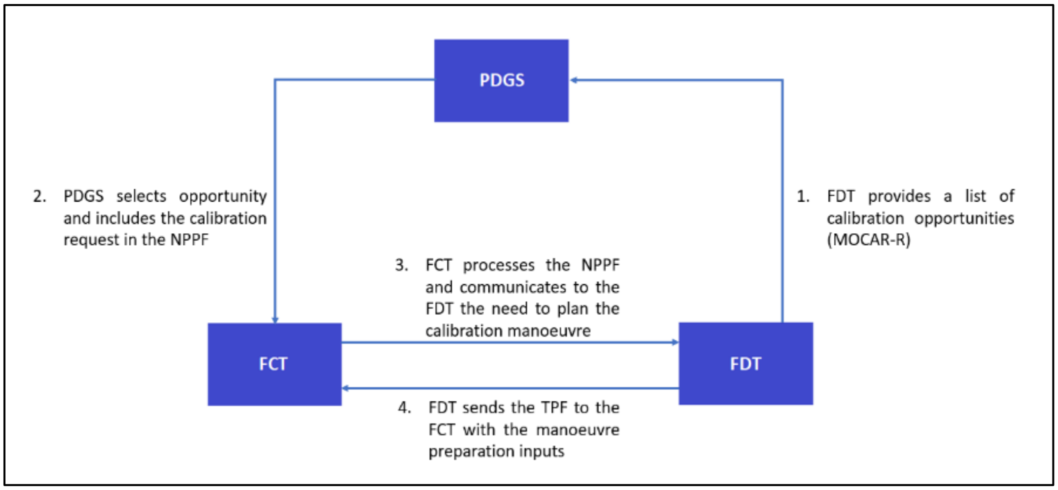

Figure 1. Cycle of events in the MSI Moon observation.

In Figure 1 it is shown that first the FDT creates the MOCAR-R and provides it to PDGS, which then chooses a calibration opportunity and includes the request in the NPPF. Then, the FCT processes the NPPF and plans the payload activities in case all the constraints are met. If the request for the calibration using the Moon is detected in the NPPF, it will be planned and the FDT will generate the TPF based on the selected opportunity within the MOCAR-O.

Once a calibration opportunity is selected, the subsequent steps are divided in payload (MSI) and platform activities. The need to make this differentiation is because PDGS requests are mostly based on geometric considerations using long-term predictions (MOCAR-R). The slew planning performed by the FDT however, is a short-term fine-tuning originating from the most recent orbit determination. In turn, PDGS selects the calibration opportunity and schedules the payload activities. For these reasons, even though the payload and the platform activities are related in this operation, their preparation is decoupled. The manoeuvre execution itself is kept under control of the FOS, as it is considered a safety critical operation.

2.1. *Detection of calibration opportunity and payload activities*

The first step is to detect and plan the calibration opportunity. As foreseen in the Sentinel-2C/D system requirements, the Moon imaging shall be done monthly when the Moon's phase angle is between 7° and 55° and it is crossing the field of view (FOV) of a single MSI central detector. It has been agreed during the design phase to target a Moon phase angle of 30°. Moreover, to avoid any impact on other subsystems and on the MSI imaging availability, the full operation should be executed during eclipse. Based on these conditions, the FDT will provide a list of opportunities to PDGS, who will then choose one of them and include it in the NPPF that is delivered every second week to the FCT. The FCT will use the file during the routine mission planning and build a stack of commands that includes the operation of the MSI for all the requests, including the Moon imaging. During the process, the request to image the Moon is detected and the FDT will generate the TPF with the parameters to plan the slew manoeuvre to point the MSI selected detector's FOV towards the Moon. The FCT will then use that TPF to generate the commands for the manoeuvre. The slew is part of the platform activities and will be further described in section 2.2.

To ensure that there are no conflicts between planned activities (e.g. orbit control manoeuvres), PDGS will communicate at least three months before the opportunity if they are planning to change the target Moon phase angle. Moreover, 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 to perform the following steps:

1. Enable specific telemetry packets.
2. Transition the MSI mode from Standby to IDLE, an intermediate mode in which all hardware modules of the MSI are switched on. After a short thermal stabilisation period, the MSI is ready for imaging.
3. Start recording instrument data into the Mass Memory and Formatting Unit (MMFU)
4. Acquire image data by switching the MSI from IDLE to IMAGE mode and back to IDLE.
5. Stop recording data into the MMFU.
6. Transition the MSI mode from IDLE to Standby
7. Disable specific telemetry packets.

2.2. *Platform activities*

Regarding the platform activities, the spacecraft needs to slew a maximum of -130° around the roll axis to point the MSI's line of sight towards the Moon. The limitation of the maximum slew angle is to avoid the star trackers being blinded if the Earth crosses their FOV and an impact on the MSI radiators. A tranquilisation time is foreseen to allow the spacecraft to reach a stable attitude and to ensure pointing accuracy before the imaging of the Moon is commanded. Such a tranquilisation period will also be considered after the back-slew and before normal MSI 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.

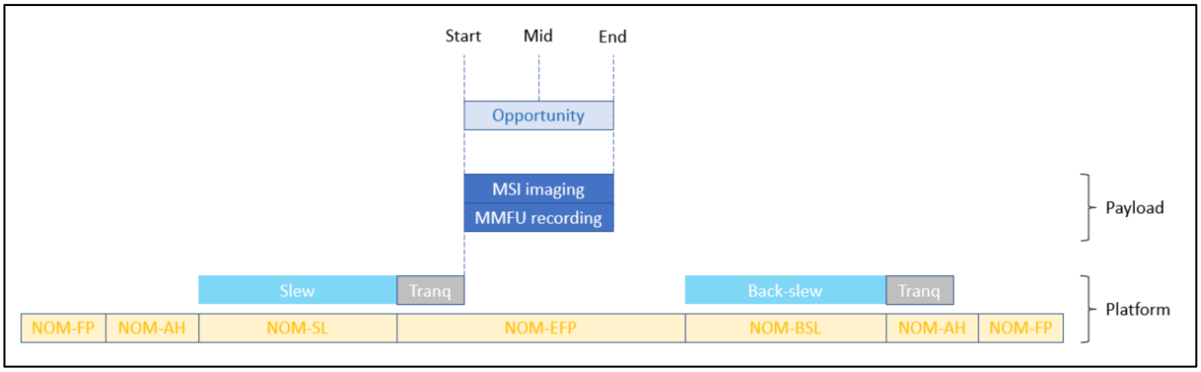

Figure 2. Platform sequence of events and AOCS sub-modes transitions.

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:

- 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 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 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: star trackers, inertial measuring units (IMU), magnetometers, magnetorquers, coarse Earth and Sun sensors and reaction wheels for attitude control, and in addition, the GPS receiver.

The slew has a duration that depends on the spacecraft roll angle. It follows a trapezoidal law with an acceleration and deceleration phase, and a phase in between at which the rotational speed is constant. The same applies to the back-slew. 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. This value 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. The two tranquilisation phases start at the end of the slew and back-slew phase, respectively.

2.3. *Coordination of Platform and Payload Activities*

The timing and duration of the different activities are predefined, as the payload and platform operations need to be precisely synchronised to not jeopardize the scientific return.

The payload's activities are also included in Figure 2. As shown, the slew around the roll axis needs to be proceeded by a tranquilisation phase to allocate time for the attitude stabilisation before MSI imaging can be started in NOM-EFP mode. 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 together with 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 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 and the MSI can start imaging only once the convergence has been reached. 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.

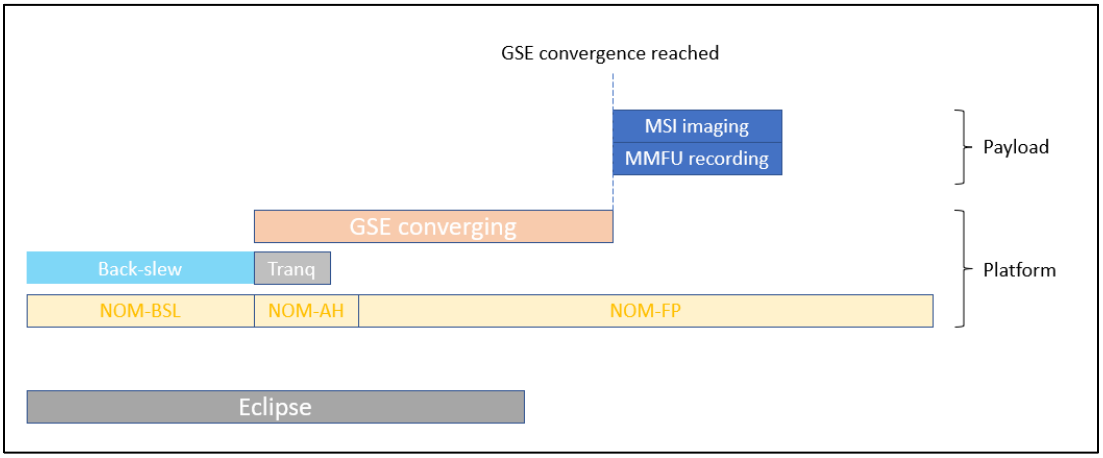

Figure 3. GSE convergence waiting period prior to MSI observation.

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 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.

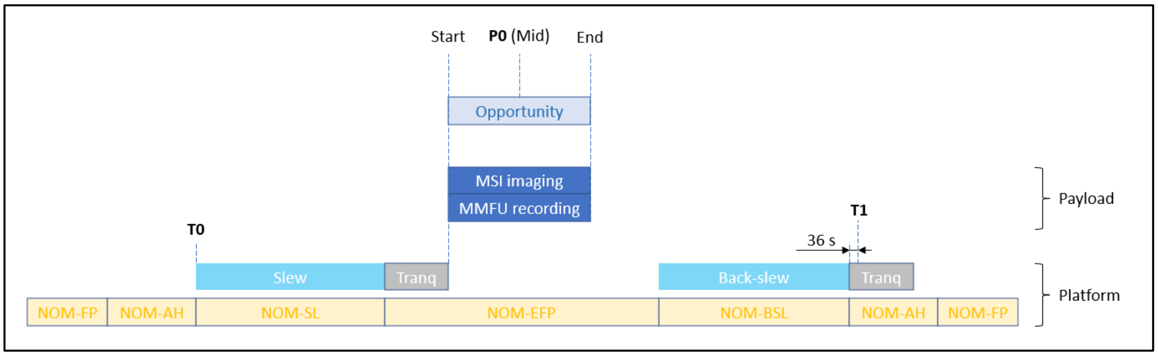

Figure 4. Reference times to plan the platform and payload activities.

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.

The sequences of time-tagged commands for the manoeuvre operation were defined in a procedure that is based on the time references **T0** and **T1** and includes the following steps:

1. Perform sanity checks on the spacecraft.
2. Disable the MTL sub-schedule ID (SSID) to prevent the related commands from executing.
3. Report MTL summary with the commands that are on-board.
4. Load the TPF sent by the FDT. Commands for the next activities are loaded:
    a. Increase the generation frequency of packets that report the status of the batteries.
    b. Increase the EOCV.
    c. Disable the yaw steering of the spacecraft, which requires an AOCS sub-mode transition.
    d. Set the target roll angle and direction.
    e. Enable the sub-mode transition that starts the slew. The transitions to EFP mode and the back-slew are triggered automatically by the spacecraft.
    f. Enable the yaw steering of the spacecraft after the back-slew.
    g. Transition to the nominal AOCS mode, NOM-FP.
5. Enable the MTL sub-schedule ID (SSID) once the operator verifies all commanding is onboard and preconditions are met.

The procedure includes a final set of steps and commands that are not time-tagged, and that instruct to perform some sanity checks after the operation and restore the EOCV to nominal values.

2.4. *Definition of support activities*

The definition of the new operational concept carries not only the definition of the files that are used to coordinate and plan the activity, but also the update of the systems to process and transfer such files. Consequently, new interfaces were needed. Indeed, the interfaces to exchange the MOCAR-R, MOCAR-O and PMCR did not exist and have been created together with Generic File Transfer System (GFTS) pollers that transfer the files from one server location to another. Once defined, the interfaces were tested and validated, thus allowing the files exchange between the three involved teams.

Further, the mission planning system has been updated to scan the NPPF in search of the request for a calibration using the Moon as a target. When processing the file, the operator will be informed about the need to prepare the activity and the FCT will pass the file to the FDT, which will parse it for the calibration request.

2.5. *Challenges and difficulties found during the operation's definition*

Defining the activity was achieved thanks to the close interaction between different teams that are spread across several countries. On the one hand, the two teams that belong to the FOS, the FCT and the FDT, are located in the European Space Operations Centre (ESOC) of the European Space Agency (ESA) in Germany. On the other hand, PDGS is located at the European Space Research Institute (ESRIN) of ESA in Italy. Two other teams participated in the definition of the operational concept. These are the designer and manufacturer of the satellites, Airbus Defence and Space GmbH, which is located in Friedrichshafen, Germany, and ESA's responsible of the project, located in the European Space Research and Technology Centre (ESTEC) in the Netherlands. Although the collaboration proved to be efficient, the coordination across teams remains one of the big challenges.

From the payload point of view, an assessment was required to decide, based on the geometry of the Sentinels' orbit and the relative position of the Moon, which detectors were most suited to be used for the calibration. Additionally, the Mission Performance Centre (MPC) performed a Moon phase/detector trade off to create conditions as close as possible to the conditions used by other spacecraft while ensuring a monthly opportunity for Sentinel-2 based on spacecraft constraints. Moreover, the precise timing of MSI activities needed to be provided, since the payload and platform activities, though decoupled, must be perfectly synchronised. For that purpose, the three reference times **P0**, **T0** and **T1** described in section 2.2 have been defined.

Regarding the platform, an assessment of the impact on all the subsystems was performed, determining that there was an impact on the GPS/GNSS, on the image processing due to the GPS/GNSS performance, and on the Electrical and Power System (EPS). An analysis on the GPS/GNSS receivers showed that with the satellite's slew their field of view could be obscured by the Earth, thus causing the number of trackable space vehicles to drop. Consequently, the GPS/GNSS units could become temporary invalid, which could trigger an on-board FDIR monitoring if this status persists over one hour. Since the Moon calibration is not expected to last that long and the return to the spacecraft's nominal attitude increases the number of trackable space vehicles, this is not considered to be a risk. However, it has been observed on Sentinel-2A and -2B that any navigation solution outages that occur whenever the spacecraft is slewing have an impact on the convergence of the GSE. The GSE is a block of the AOCS software that provides attitude and gyro bias estimates using the IMU rate and up to two star tracker quaternion measurements that are used only on-ground for image and geolocation processing. Consequently, some waiting time must be allocated between the slew and the start of the MSI imaging as mentioned in section 2.3. This allows the GSE to converge in case of an invalid navigation solution and minimises the impact on the PDGS processing. The definition of a MSI unavailability phase is the result of an analysis on historical Sentinel-2A and -2B data and was estimated to last 897 s after the re-entry into the NOM-FP sub-mode. During this time, the prediction is that the GSE convergence is not guaranteed and will be better quantified based on the in-flight observations.

Another challenge was to determine the impact of a spacecraft slew and MSI imaging on the EPS. Several simulations were performed and concluded that in the worst-case scenario an undervoltage due to the increased power demand, would cause a software-driven reconfiguration of the spacecraft, disconnecting the non-essential loads from the batteries (SW DNEL). This can be avoided by increasing the EOCV in advance, i.e. performing battery boost charging. However, in the long term this has a negative impact on battery lifetime. For that reason, it was decided that a small increase of the EOCV from 32 V to 32.6 V is safe enough to avoid an undervoltage and also minimises the impact on the batteries' lifetime. Nevertheless, the EOCV needs to be decreased to its original value during the first nominal pass after the activity, provided that the status of the spacecraft is confirmed to be nominal.

The secondary payload of Sentinel-2, the Optical Communication Payload (OCP) requires an accurate pointing of its laser terminal, which cannot be achieved while the spacecraft is slewing or not holding the nominal attitude. Even though this has no impact on the overall safety of the spacecraft, the usage of the OCP will not be planned during a time range coinciding with the MSI calibration operation.

3. Current status and way forward

The challenge of the MSI calibration by means of imaging the Moon is not only the definition of the operation itself, but also ensuring that it is safe enough to be executed on the Sentinel-2 missions without introducing any risks. The deployment of the operation can be divided in three different phases, starting with the definition of the operational concept, and required support interfaces and files. This is followed by the on-ground and subsequent IOCP testing on Sentinel-2C and finally by the introduction of the new calibration into the routine phase activities.

All the required input and output files have been defined and tested during the on-ground Sentinel-2C System Validation Tests (SVTs). During the IOCP, testing will proceed in space and introduced to the routine operations of Sentinel-2C. A dedicated test and validation of the ground interfaces will be required in case the same activity will be implemented for the other satellites of the constellation.

The immediate next steps are to run the Ground Segment Validation (GSV) tests and the IOCP activities for Sentinel-2C. During the GSV tests the correct implementation of the PDGS-FOS interfaces and the overall planning concept will be verified. Following the GSV tests, an in-orbit validation campaign will be planned and executed once Sentinel-2C is in orbit. Such phase will be used to streamline the operation and processes and to ensure the spacecraft behaviour is in line with the predictions. For that purpose, four types of tests should be performed during the IOCP:

- Slew test: the platform part of the operation will be executed to check the slew, the mode transitions, and the impact on the GNSS.
- MSI modes test: the payload part of the operation will be executed to verify the MSI mode transitions and the use of the required tables.
- One-off dry run: the full activity will be executed with both payload and platform commanding by FOS.
- Optimisation runs: additional Moon acquisitions implementing lessons learned from first run to streamline operations for future routine use with amendments for performance and margin optimisation. One of the

variables that might change in this phase is the reference time **T1** that was defined to 36 s in section 2.3. This value has been measured empirically for slews around the yaw axis in the frame of manoeuvre executions. Given the different inertia properties around different axis, the roll slew could require a different interval than the yaw slew.

4. Conclusions

The use of the Moon as a calibration target for the Sentinel-2C MSI is a new operational concept whose definition, constraints and technical challenges, have been described in this document. Since the activity was not considered in the development phases of Sentinel-2A and -2B, the main constraint of the implementation of the operation in Sentinel-2C was to avoid a change in the satellite's design. Apart from this one, there were other limitations that shaped the definition of the operation, such as the need to perform the activity in eclipse, or the requirement to target a Moon phase of 30°.

The process to define the operation implied the interaction between several teams that are located in different European countries, reviewing the impact on the satellite and the operations of the activity and the definition, test and validation of various interfaces. It also required to split the operation in two processes -payload and platform activities- that must be precisely synchronised to ensure the correct pointing of the spacecraft when the data acquisition takes place. To complete a safe operation, a set of support activities, such as battery boost charging, have also been considered.

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. Consequently, the operation has been tested on ground during the S2C System Validation Tests and will be tested in space during the In-Orbit Commissioning Phase, both to validate the sequence of activities and to fine tune the operation. Although it has not been considered for Sentinel-2A and -2B, the operation has been defined taking into account that it could be adopted by these two satellites in the future.

Acknowledgements

The definition of the operation to calibrate the 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.

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