SMOS "Long ECM": a successful CNES–ESA joint operations prepping

Benoit Léger[a]*, Saïd Haouchine[a], Sonia Aït Zaïd[a], Eva Jalabert[a], Thomas Paulet[b], José Luis Ramírez Gil[c], José María Castro Cerón[d], Jorge Fauste[e], Sabine Amram[f], Olivier Rouat[f]

[a] *Centre national d'études spatiales (CNES), 18 av. Édouard Belin, F-31401 Toulouse, France; l-proteus-bord@cnes.fr*
[b] *CS Group, 6 rue Brindejonc des Moulinais, F-31500 Toulouse, France*
[c] *European Space Operations Centre (ESOC), SERCO for ESA, D-64293 Darmstadt, Germany*
[d] *European Space Astronomy Centre (ESAC), ISDEFE for ESA, E-28692 Villanueva de la Cañada (Madrid), Spain*
[e] *European Space Astronomy Centre (ESAC), ESA, E-28692 Villanueva de la Cañada (Madrid), Spain*
[f] *Thales Alenia Space, 5 all. des Gabians, F-06156 Cannes, France*
* corresponding author

Abstract

We describe the definition of a new concept in operations for *SMOS*: "*Long ECM*". It has been developed to mitigate a payload thermal anomaly that appeared in the mission six years after launch. This anomaly has worsened during the past few years and is now closing on impeding payload operations for two well identified time periods each year. To mitigate the potential effects of this anomaly, we utilise an existing pointing mode called ECM (External Calibration Manoeuvre), regularly used in flight to calibrate the payload, but on this occasion with an extended duration of a few days (instead of a few minutes), what allows for the payload to cool down. The definition of this new "*Long ECM*" mode —ahead of the thermal anomaly compromising regular operations— has provided a clear way forward to maintain and/or extend the viability of the mission.

SMOS is a joint CNES-ESA mission that performs global observations of soil moisture over land and salinity over oceans. It carries a single instrument, MIRAS, an *L* band interferometric radiometer. Initially designed for five years, the satellite is already in its fourteenth year of service. In mid-November, and towards the end of January, every year, the temperature of one of the segments of MIRAS arms systematically increases above its operational control point (22° C), likely due to degradation of the insulation blankets and radiator emissivity, combined —around these dates— with higher elevation of the Sun over the MIRAS antenna plane. Peak temperatures to date, during these two periods, are far from dangerous physical limits. Yet these limits could turn up in a few years' time, threatening operations and limiting mission duration.

Keywords: *SMOS*, AOCS, temperature increase, ageing, risk mitigation manoeuvre

Acronyms/Abbreviations:

AOCS: Attitude and Orbit Control System
ECM: External Calibration Manoeuvre
FDIR: Failure Detection Isolation and Recovery
FOS: Flight Operations Segment
FOV: Field Of View
LICEF: Light Weight and Cost Effective Front End
MIRAS: Microwave Imaging Radiometer using Aperture Synthesis
OBSW: On Board SoftWare
PRESTO: PRoteus Engineering Simulator for Tests and Operations
PROTEUS: Plateforme Reconfigurable pour l'Observation, les Télécommunications Et les Usages Scientifiques
RMM: Risk Mitigation Manoeuvre
SMOS: Soil Moisture and Ocean Salinity
SOGS: Satellite Operations Ground Segment
STR: Star Tracker

1. **Introduction**

Launched 2nd November 2009, ESA's *Soil Moisture and Ocean Salinity* (*SMOS*) satellite is the second of the Earth Explorer missions in orbit, and performs global observations of soil moisture over land and salinity over oceans (Figure 1). The spacecraft is jointly operated by CNES and ESA space agencies. CNES is in charge of platform operations while ESA operates the payload. The satellite carries a novel, *L* band, interferometric radiometer (MIRAS) to capture "brightness temperature" images from which maps of ocean salinity and soil moisture are further derived. By consistently mapping two important components in the water cycle it is advancing weather and climate models. With an initial mission duration of three+two years, *SMOS* has surpassed thirteen years of operational service. The mission has already been extended three times (years 2014, 2017, and 2022), and it is currently planned until the end of 2025. *SMOS* is a 3-axis stabilised satellite, operating in a dusk-dawn Sun synchronous, nearly circular, polar orbit of 763 km mean altitude, with an inclination of 98.4° and local solar time of 18:00 descending. It has been built on a turnkey platform (PROTEUS), developed by Thales Alenia Space France. *SMOS* is operated as a collaboration between CNES (Toulouse), which controls PROTEUS, and ESA-ESAC (Madrid), which plans and controls the MIRAS operations**.**

Figure 1. Artist impression of the *SMOS* satellite

The *SMOS Ground Segment* is spread across two main sites: for PROTEUS the *Spacecraft Operations Ground Segment* (SOGS) and for MIRAS the *Flight Operations Segment* (FOS). SOGS consists of the *Command and Control Centre* (CCC) and the *S* band station network. CCC functionality comprises tele-commanding, orbit and attitude processing, and the monitoring of platform housekeeping telemetry. All tele-commands are up-linked via SOGS, using the *S* band ground station network provided by CNES; the network acquires the housekeeping telemetry too. SOGS provides FOS with *S* band housekeeping telemetry, as well as orbit and attitude auxiliary files. FOS consists of payload operations and the *FOS Ground Segment*. FOS functionality comprises MIRAS payload operations and planning, and coordination of the platform operations led by CNES and the payload operations led by ESA. FOS performs MIRAS commanding and health monitoring. These involve weekly commanding for planned activities and reception of housekeeping telemetry. Manual, unscheduled commanding is done as well for specific payload activities and/or anomaly recovery. See Figure 2 for the principal ground segment systems.

In this paper, we examine the current status of a thermal anomaly that arose in MIRAS after six years of operations, we review all the mitigation scenarios initially considered and —most important— the course followed by CNES and ESA to decide on the final optimal solution. Further, we illustrate its successful implementation into operational procedures for both platform and payload. Last, we exemplify the good working relationship —and deep coordination capabilities— of the two teams that have been running *SMOS* operations for well over thirteen years with notable achievements. Our paper is organised as follows. Overviews of both platform and instrument are given in Sections 2 and 3 respectively. The thermal anomaly is described in Section 4, and in Section 5 we consider various mitigation scenarios. Section 6 covers the simulations. Section 7 discusses the implications of the long ECM for PROTEUS, and analyses risk mitigation manoeuvres. We conclude in Section 8.

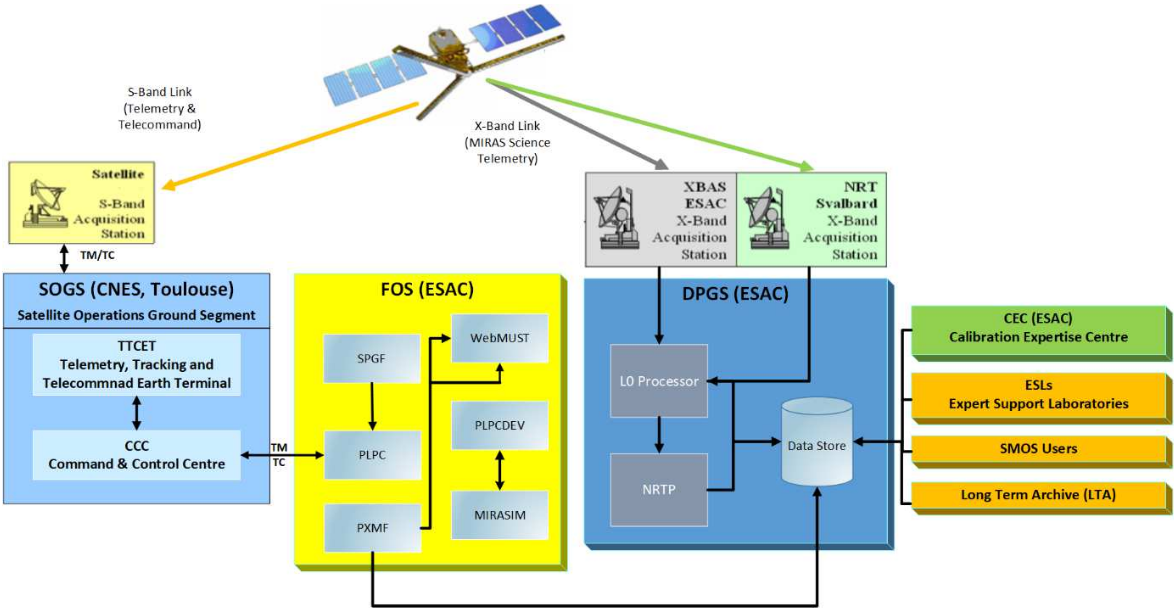


Figure 2. *SMOS* Ground Segment overview

2. Spacecraft platform description

The *SMOS* platform is based on the PROTEUS (***P**lateforme **R**econfigurable pour l'**O**bservation, les **T**élécommunications **E**t les **U**sages **S**cientifiques*) bus, which have been utilised by CNES in five different satellites: *Jason2*, *Jason3*, *Corot*, *Calipso*, and *SMOS*. This Platform (Figure 3) has a high level of flexibility and adaptability to in-flight modifications. The design is based on two half-satellites (process module), PMA and PMB, with some dedicated equipment in each half and with other components shared between the two half-satellites (**s**ee Figure 4). The platform was intended for a nominal lifetime duration of five years. However, *Jason2* spent over 12 years in orbit, *Calipso* is still flying after 15 years, and *Jason3* and *SMOS* continue flying as well. *SMOS* has been orbiting Earth since Nov 2009. These figures pay tribute to the robustness of PROTEUS.
Redundancy is present in all its apparatuses, and *SMOS* has never triggered a safe mode since launch. Energy reserve is excellent, with remarkable margins. A significant surplus of propellant is available too, and last analysis showed a possible re-entry duration ranging from 8 to 11 years, in compliance with the French Space Act, which requires a reentry for low-orbit missions within 25 years).

Figure 3. PROTEUS platform

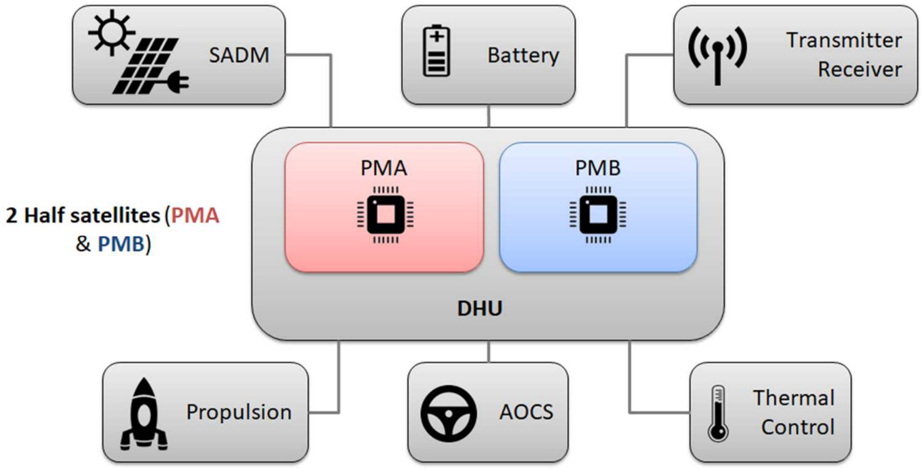


Figure 4. Layout of the PROTEUS platform

Station keeping thrusts are executed about every 4 months to counter atmospheric drag effects and ensure equatorial phasing on a specific mission grid. This orbit warrants the satellite to always be illuminated by the Sun; maximum light incidence on solar arrays is achievable using the right attitude guidance law. *SMOS* base pointing goes as follows: the payload is oriented towards local nadir with a 32° angle in track offset, the solar panel axis is mostly kept collinear with the satellite velocity, and arrays rotate to maximise illumination. A small yaw steering compensates for Earth rotation affecting data.

3. Payload description

The *SMOS* payload is an *L* band, 2D interferometric imaging radiometer with a Y-shaped, three arms, synthetic aperture antenna. Payload structure is split into a fixed, central hub, 1.3 m high, and three arms extending up to the 8 m instrument diameter (deployed configuration). It comprises 69 LICEF receivers (*Light Weight and Cost Effective Front End*) distributed along the three arms, and the central hub. The three arms have an angular separation of 120º and they are denominated A, B, and C (Figure 5). The plane defined by these three arms is called the MIRAS antenna plane.

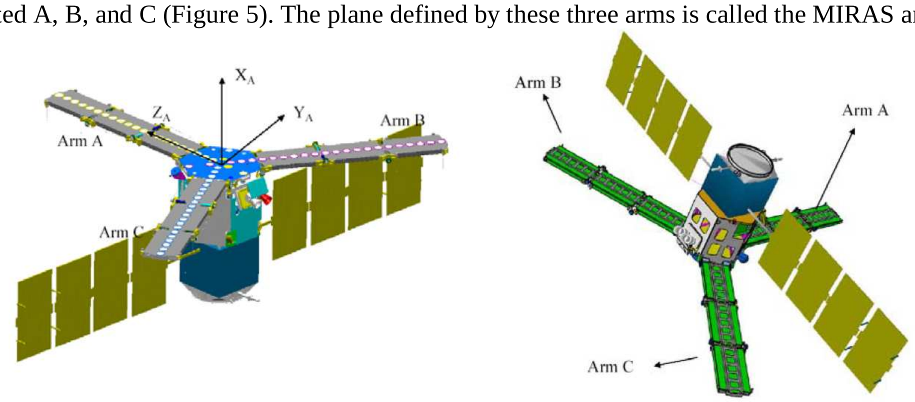


Figure 5. *SMOS* axis orientation and arm nomenclature

Each arm is made up of three segments, each containing six different LICEFs. MIRAS central hub is located underneath PROTEUS. It houses another 12 LICEFs, plus three Noise Injection Radiometers (NIRs), together with the payload on-board computer (CCU), and some other electronic equipment. The payload measurement principle is based on the cross-correlations between pairs of signals acquired by different antennas. The instrument can measure the scene with all the receivers in the same polarisation (which alternates horizontal/vertical; dual-polarisation mode), or can follow a sequence with various LICEFs in different polarisations.

An on-board, active thermal control over each MIRAS arm segment/hub sections (a total of 12 separated duty cycles) maintains the payload around 22° C. A set of six MIRAS thermal sensors, combined with two separated (prime/redundant) PROTEUS sensors, are located along each of the arm segments.
The physical principle of the mission is the interconnection between the Earth surface electro-optical properties (specially emissivity) and soil moisture/ocean salinity (among other parameters, like the direction of observation or the frequency). In particular, humidity and salinity decrease emissivity (ground and sea respectively), changes being especially notable in the *L* band (1.4 GHz, ~21 cm).
Mission data availability is highly remarkable since more than 99.8% of the overall possible science data has successfully been acquired, processed and distributed to the science community. This has been possible due to the lack of significant payload and platform anomalies and the good and smooth coordination between CNES and ESA operational teams. Initially foreseen for five years and now smoothly running for more than thirteen, *SMOS* has provided to the science community with a unique availability of long time *L* band data series. This long data availability allows the science community to analyse and to verify trends that can be used to assess evolutions on different areas such as climatology, weather forecast modelling and climate change. Because of this long data availability, new science products such as ice and wind products have also been created. Far beyond the initial science expectations, new applications have also been discovered in different science fields such as the measurement of the Sun flux in *L* band that provides a unique spectral window to better characterise solar activity and Space Weather features.

4. **MIRAS Arm A thermal anomaly**

Nominal *SMOS* attitude is such that MIRAS Arm A is always orthogonal to the orbital plane and the payload boresight tilted 32° respect the nadir direction. This nominal attitude causes the sun direction vector to rotate around Arm A describing a cone once per orbit in about 100 minutes (Figure 6).

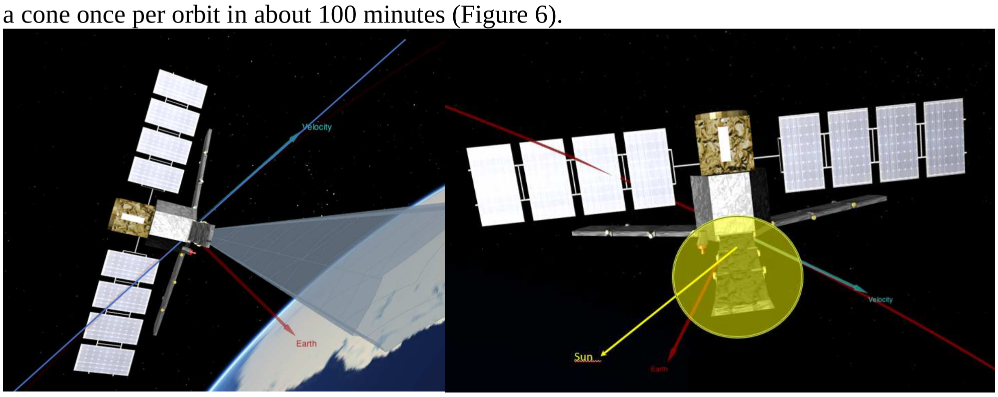


Figure 6. *SMOS* nominal attitude configuration and Sun "cone" around arm A

Because of its orbital inclination at 98° respect the Earth equatorial plane, the amplitude of this cone yearly oscillates from the ecliptic inclination, 23°, ± 8 degrees, i.e. from 0° to 31°. Maximum amplitude of this angle and therefore maximum Sun elevation over MIRAS antenna plane, is reached at Winter Solstice around 21st of December. Another relative maximum of 15° is reached around Summer Solstice and two annual minima of 0° on the 13th and 27th of August (Figure 7). Because of this annual variation, thermal duty cycles in each of the MIRAS segments change around the year but mainly over arm A that fronts Sun direction. This variation is almost neglectable over both arms B and C which are mostly obscured by MIRAS hub and PROTEUS platform.
Because of its orbital inclination, ascending node position at 06:00 hours and orbit elevation around 763 Kms, an annual eclipse season over north pole latitudes is always happening from 10-11th of November until 29-30th of January. Around 1100 eclipses occur during each of these seasons, one eclipse per orbit with a maximum duration of about 1059 seconds for the ones occurring around the 20-21 of December (Figure 8). Since Sun elevation over the antenna plane is monotonically growing from early September until Winter solstice, duty cycle of arm A also decreases but because of the start of the eclipse season this effect gets temporarily reduced during that period.

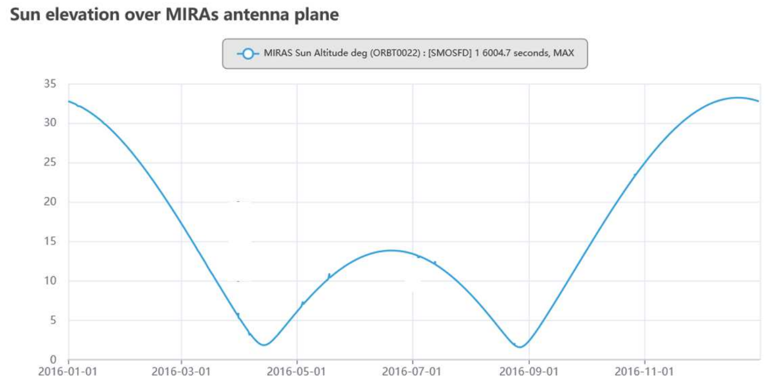


Figure 7. Annual maximum Sun elevation over the MIRAS antenna plane

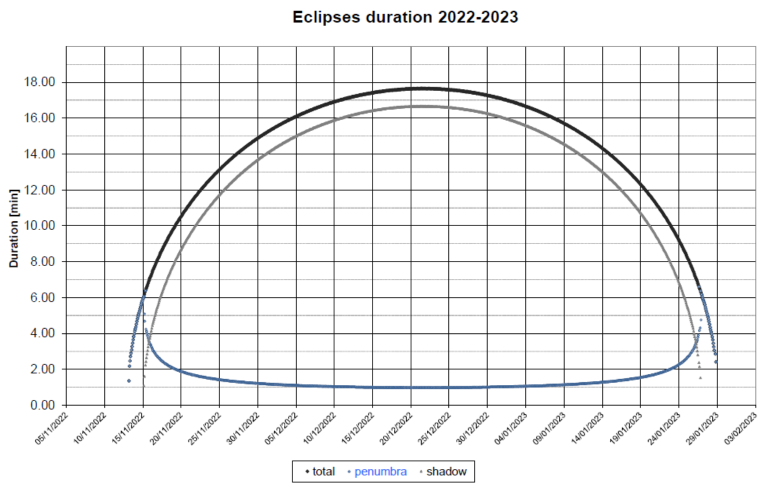


Figure 8. Typical duration of the *SMOS* eclipse season

In the first years of mission there were no significant differences on the duty cycles for each of the MIRAS arm segments. Nevertheless, starting in 2017 (8 years after launch), a first significant decrease in the duty cycle of segment A1, the one close to the instrument hub, was clearly observed. This decreasing trend grew further during the following years reaching a point in 2019 where it totally stopped for several consecutive weeks and until the end of the eclipse season. This decrease is clearly seen in Figure 10 where the evolution of the duty cycle per orbit is displayed for the last 8 years of mission from sometime before the start of the eclipse season until the mid of it in December. On the top side of that graphic it is possible to see that the duty cycle for the first two years is continuous while progressive discontinuities further appear in the next years. Following years, the duty cycle of segment A1 stopped earlier and earlier (Table 1) with the side effect that temperature of segment A1 increased beyond instrument control limits.

Typical evolution of the MIRAS segment A1 temperature during two *SMOS* consecutive orbits is displayed in Figure 9. The two selected orbits are part of the usual *SMOS* eclipse season from mid-November to end January. In this figure it is clearly seen that highest temperatures are reached over north arctic regions but they immediately drop at the start of the eclipse period (pink square function)

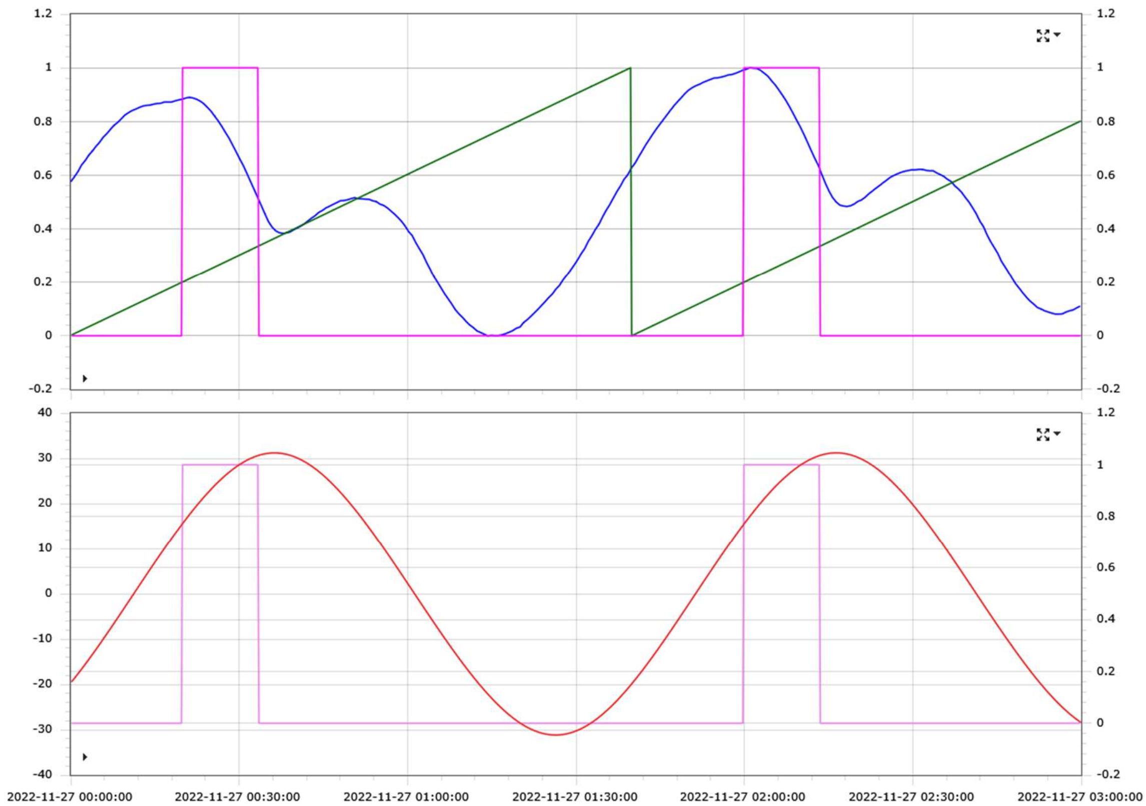


Figure 9. A1 temperature evolution along two consecutive *SMOS* orbits (blue) versus Sun elevation over the antenna plane (red), and eclipse occurrences in an orbit (pink).

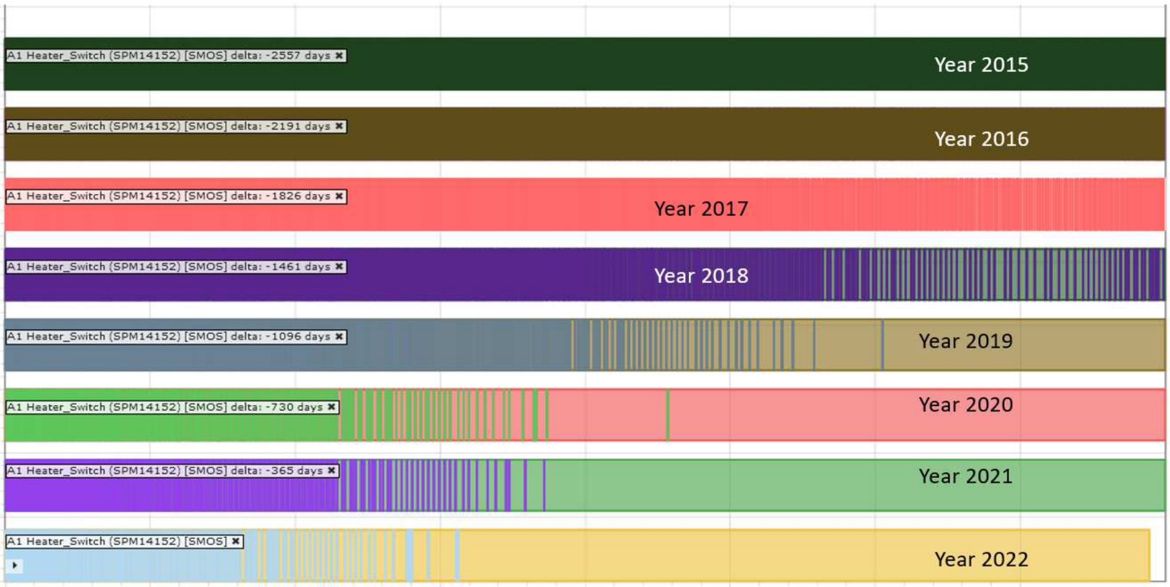


Figure 10. Duty cycle evolution in MIRAS segment A1

Table 1. Time periods when MIRAS A1 duty cycle was off

MIRAS A1 duty cycle stops	*MIRAS A1 duty cycle restarts*	*Nº of days off*
04/11/2019	*09/02/2020*	*97*

29/10/2020	*10/02/2021*	*104*
28/10/2021	*14/02/2022*	*109*
26/10/2022	*17/02/2023*	*115*

When thermal control of segment A1 stops, temperature also increases for orbital periods when the Sun is above the antenna plane which also corresponds with higher and positive latitude orbital positions. The combination of this duty cycle cease plus the eclipse season created two temperature peaks once just immediately before the start of the eclipse season and another one just at the end (Figure 11) The first peak, around the 10th of November, is reached because on those days the Sun elevation, around 23°, is still increasing way to its yearly maximum but then the start of the eclipse season obscure the Sun around *SMOS* higher orbital positions (Figure 7). These orbital positions correspond with the ones where the Sun also reaches its higher elevation over the MIRAS antenna plane triggering a cool down of MIRAS A1 segment. The second peak in January is reached because at the end of the eclipse season the Sun elevation is still very high although it is getting towards its next yearly minimum by mid-April. The earlier the duty cycle stops, the higher the temperature of these two peaks will also be. This is because temperature will earlier diverge from its thermal control point at 22° having more time before reaching the start of the eclipse season on the 10th of November.

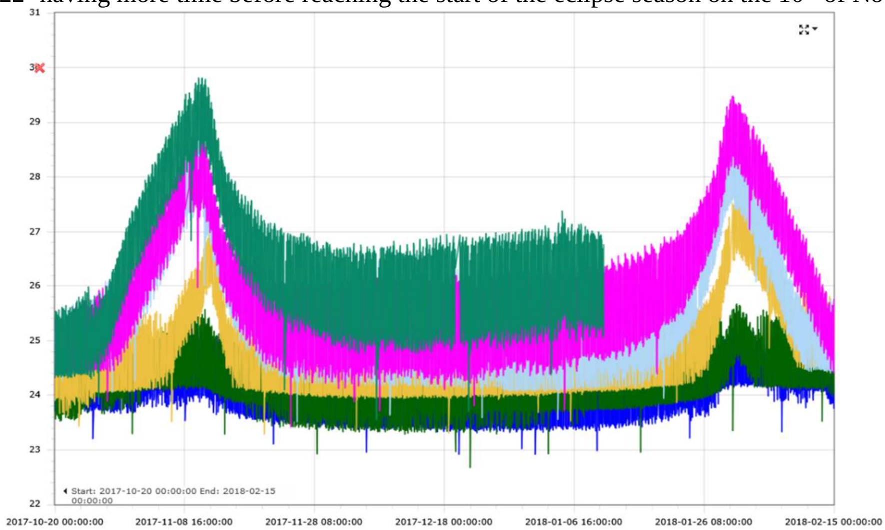


Figure 11. Segment A1 temperatures with duty cycle off (2017—2022)

The future evolution of this event and its possible consequences at payload health & safety level, triggered an early alert on both CNES and ESA operations teams, in the way to find a possible solution to mitigate the anomaly and to avoid or to skip those two thermal peaks in years to come. Further increase of these two peaks may exceed CMN thermal qualification temperatures at 40 degrees but also certain higher temperature ranges might affect instrument calibration and science data quality.

5. Thermal mitigation scenarios: selection of *Long ECM*

Several possible scenarios were initially selected trying to decrease the Sun elevation over the MIRAS antenna plane around those two thermal peaks (Table 2). Some of them considered possible orbit and attitude changes while others only considered payload configuration changes. Among the ones on the first group, it is worth to mention:

- To permanently change *SMOS* orbit inclination to decrease the maximum possible elevation of the Sun over the antenna plane.
- To decrease *SMOS* orbital elevation to have longer eclipse seasons and therefore an earlier cool down of segment A1.
- To temporarily rotate *SMOS* around its roll angle or its velocity vector.
- To temporarily point *SMOS* into an inertial external position such that the Sun will be tangential to the MIRAS antenna plane (Sun elevation close to zero degrees)

For the second group of actions the only one initially considered was to switch-off the instrument around the two temperature peaks.

Due to science data continuity and availability requirements, we rapidly avoided the "payload switch off" option. Switching off the payload requires a long transition period before reaching nominal values again and affecting good quality's science data. A certain risk may also exist for this option since the instrument has never been switched off in more than 13 years of operations.

The first two orbital options were early discarded because of their minimum added value for the anomaly and its uncertainty and costs in terms of spacecraft hydrazine. Also those orbital changes would have modified the slow natural drift of the orbit which would have made the new data non easy to compare with previous years of similar series.

Finally, we had 3 remaining options: To temporarily rotate *SMOS* around its roll angle or its velocity vector, or to temporarily point *SMOS* into an inertial external position. The third one is similar to a regular manoeuvre used to calibrate the instrument, whose name is "ECM" for "External Calibration Manoeuvre". This manoeuvre is performed every two weeks, during a few minutes, in order to point the instrument towards cold space. The idea was to use the same kind of manoeuvre, but for a much longer duration (few days), and with a different target attitude. Unlike the two other options, it allows:

- To use the same Flight Dynamic tool developed before launch, avoiding extra SW costs development
- To be confident in the feasibility of the manoeuvre from Platform point of view, as it looks just to extend the duration of the ECM

The "Long duration ECM" was born. But we still had to confirm that we could decrease the temperature, and that the satellite could withstand such a long inertial attitude which will be described in the next sections.

In order to mitigate the issue and at the same time satisfy the science community, we worked with a strong cooperation between ESA and CNES as we are in the same boat thanks to the excellent collaboration built for 13 years!
Our guidance was: Science is our priority and satellite safety is our responsibility. These two basic assumptions allow us to work together in the same way and do our best to find a good and safe solution with a minimum of mission unavailability.
ESA Project Manager coordinated regular joint meetings to closely follow the topic and the two CNES and ESA teams worked on it with industry support.

6. MIRAS thermal simulations in long ECMs

Between all possible mitigation manoeuvres, Long ECMs seemed the most suitable one to the needs and it was clear that all of them could achieve a temperature decrease, but a better understanding of the real effectiveness of the manoeuvre on the A1 segment temperature was needed to properly evaluate this option. To have an estimation of the expected temperature decrease it was critical from the beginning to assess the manoeuvre effects since the real cause of the temperature increment was not initially understood.
Therefore, it was clear that an agile manoeuvre and thermal simulator was required to have an estimation of the temperature decrease. Additionally, with such simulator other aspects of the manoeuvre could be evaluated, like the ground station contact to estimate MIRAS mass memory data dumps, and the possible usage of the data taken during Long ECM.
The needs of a quick and flexible simulator to test and estimate the effects of Long ECMs and other possible manoeuvres evolved in a small project to develop a simplified thermal model of the affected segment using the original spacecraft thermal model as a baseline. Mathematical and physical models developed in the early phases of the mission and instantiated in the ESATAN thermal simulator, would therefore need further simplification and adaptation to the needs of the FOS operations team. This model was originally used to design and validate the satellite thermal control and to correlate the test results with numerical results and real telemetry. From this model, the thermal nodes and their radiative and conductive couplings will be imported and stored in a matrix data structure to later iterate over them and to solve dynamically the thermal balance equation during a theoretical Long ECM.
The selection of the simulation date was based on the temperature profile on segment A1. The temperature peak is reached just before the eclipse season starts, around 12th of November of 2021. This would be the date when the manoeuvre would take place.

Mathematically, the differential equation to be solved is the thermal balance in the segment. Applying discretization techniques, the equation can be numerically solved in a finite number of points of the segment and obtain a map of temperatures for each instant of the simulation.

$$[C] \cdot \frac{d\overline{T}}{dt} = [GL] \cdot \overline{T} + [GR] \cdot \overline{T}^4 + \overline{Q}$$

Where the [C], [GL] and [GR] are constant matrices, and its values are extracted from the correlated geometrical model developed in ESATAN (Figure 12)

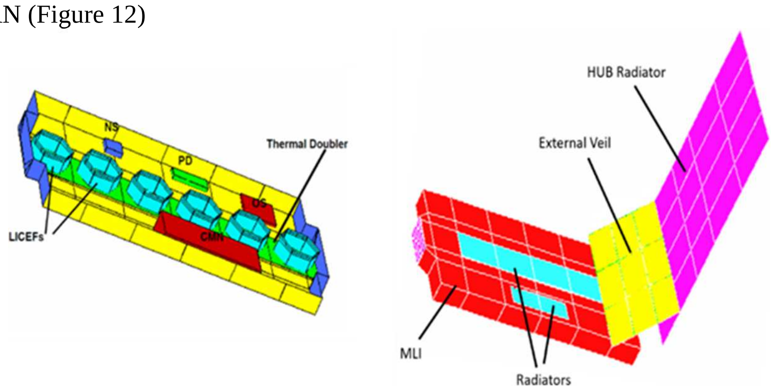
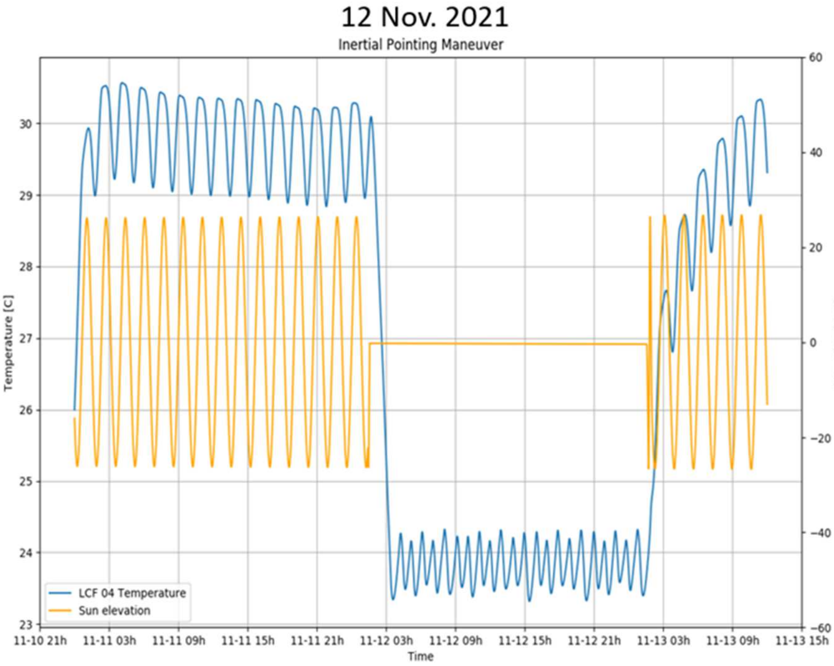


Figure 12. ESATAN image of the simplified model

The main purpose of the Long ECM scenario is to point the spacecraft at a certain selected inertial attitude such that the Sun will stay almost coplanar with the MIRAS antenna plane for several hours or even days. By doing that, the solar radiation over A1 radiators is cut down and segment A1 will be significantly cooled. In this condition, the spacecraft is constantly pointing to the same inertial coordinates and rotating around Arm-A (spacecraft +Z axis). This situation can be reached if a certain inertial pointing over the sky is selected such that the angle between Arm-A and the Sun vector is close to zero. This type of inertial pointing can be obtained in the same way as normal NIR calibrations currently performed in operations i.e., simple spacecraft rotations around Arm-A (spacecraft +Z axis). For normal calibration manoeuvres, the duration of the inertial pointing is rather short, 8 minutes and the Sun elevation can be maintained very constantly during the whole inertial period. In the case of a long calibration manoeuvre and due to the Earth translation movement around the Sun, the angle between Arm-A and the Sun will suffer from a constant drift of almost one degree per day. Nevertheless, this natural drift will have a negligible influence on the A1 thermal stability and its temperature evolution. That's the reason why a fixed inertial pointing should be enough to achieve the cooling goals of the manoeuvre.

After several simulations and correlations of the adapted model with real spacecraft telemetry, a theoretical Long ECM was simulated starting on the 12th of November 2021 at 00:00:00z with a duration of 24 consecutive hours (Figure 13). The required inertial pointing to hold the Sun as close as possible to zero degrees' elevation on that date was obtained solving the geometrical problem given by the normal vector plane and the sun vector.



ETO:	2021-11-12T00:00:00.0
Time length:	24 h
Inertial Coordinates:	R.A.=114.30 Dec.=7.46
X Band Passes	ESAC: 1 pass (~ 200 s) SVALBARD: 1 pass (~ 490 s)

Figure 13. Temperature evolution in segment A1 during a *Long ECM*

The simulation results show that the segment can be **cooled down in less than 2 hours and 10 minutes**. After that, the MIRAS active thermal control switches back on and keeps LICEF A04 temperature stable at 24 °C (around 22 °C average temperature for the rest of the segment). After the return manoeuvre, a new transient state will take place for approximately 12 hours (around 7 orbits) and until a new thermal equilibrium is again reached at 30 °C. As it has already been mentioned, while the spacecraft is in this long "calibration" scenario, the transmission antenna pointing is constantly rotating and therefore its attitude will not always be the right one to transmit Science data. The FOS model also computes any suitable *X* band pass where spacecraft orientation fits the right Earth antenna position. For this simulation, one pass over ESAC with an approximate duration of 200 seconds, plus another one over SVALBARD, of 490 seconds, will only be possible. Since MIRAS Mass Memory is overwritten once every 26 hours and since the duration of the long calibration for this simulated case is of 24 hours, this guarantees that no data will be lost. At the same time, potential usability of the scientific data in these conditions is uncertain, because payload scenes will constantly alternate from Earth to sky views.

On the other hand, the same simulator was used to analyse other possible manoeuvres, i.e., rotations around the velocity vector and changes in the roll angle. The results show that the temperature decrease is proportional to the change in roll angle or the rotation around velocity vector. All the given scenarios achieve the target of cooling A1 segment and keep the segment between 24 °C to 25°C.

Even if the other three scenarios imply changes on the instrument configuration, they are easy to implement from payload point of view but not from platform side. Angle rotations around either spacecraft velocity vector or roll angle seem both feasible and with similar thermal results. Among all the possible rotations, the -10° rotation looks a good compromise but rotations around the velocity vector seem easier to implement from a platform point of view. Nevertheless, long external calibration manoeuvres represent a simple and elegant solution which at the same time is easy to implement from a platform point of view.

Table 2. Summary of the different mitigation scenarios

	GROUND SEGMENT IMPACT	TEMP MITIGATION	MIRAS OPS RISK	X BAND COVERAGE LOSS	DATA IMPACT
LONG ECM	Medium	High	Low	Medium	High
ROLL ANGLE –5°	None	Low	Low	Low	Medium
ROLL ANGLE -10°	None	Medium	Low	Low	High
ROLL ANGLE -15°	None	High	Low	Medium	High
VELOCITY VECTOR R. -5°	None	Low	Low	Low	Medium
VELOCITY VECTOR R. -10°	None	Medium	Low	Low	High
VELOCITY VECTOR R. -15°	None	Medium	Low	Medium	High
SWITCH OFF ARM-A	None	Too High	High	None	Too High

7. Platform implications and risk mitigation analysis for ECMs

7.1 *Preliminary analysis*

As soon as the Long ECM was chosen as the best option from payload and platform point of view, a first batch of tests were performed at CNES with the “PRESTO” simulator software to have a first idea of the feasibility of the Long ECM option.
Let’s first explain how the attitude measurement is made for Proteus satellites: the on-board attitude estimation process is based on a gyrostellar hybridization (Figure 14):

1. Q_I_SL_updated() is the last known attitude quaternion
2. Using gyrometers’s angular rates measurements, the last known attitude quaternion is propagated to the current time: Q_I_SL_est()
3. The Star Tracker (STR) estimates the satellite attitude quaternion, which is then also propagated to the current time using gyrometers’ measurements: Q_I_SL_meas_est()
4. The difference between the two quaternions Q_I_SL_est() and Q_I_SL_meas_est() is called innovation.
5. The innovation is compared to a threshold:

- If the innovation is below the threshold, the Kalman filter combines the two quaternions to compute the final attitude quaternion at the current time: Q_I_SL_updated(
- If the innovation is above the threshold, the quaternion coming from the STR is discarded, and Q_I_SL_updated(= Q_I_SL_est()

If no STR quaternion is available, the attitude is propagated using gyrometers’ angular rate measurement.

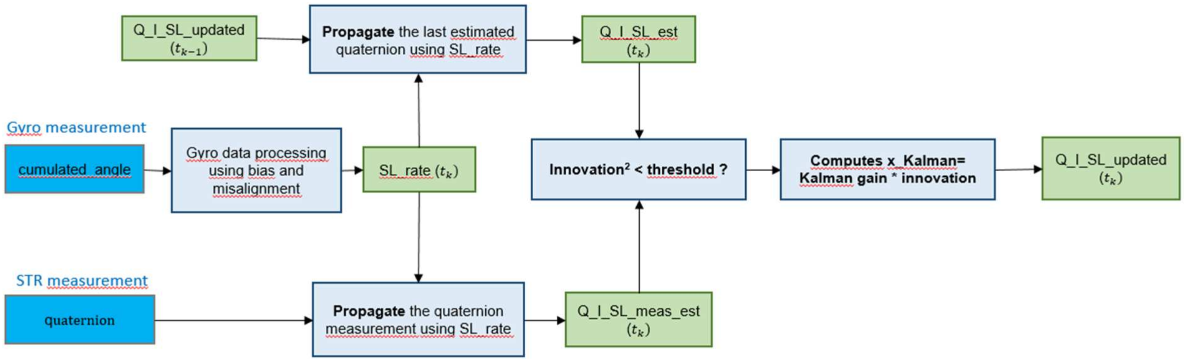


Figure 14. Simplified attitude estimation for PROTEUS satellites

Two main simulations have been performed:
(1) Case A: in order to perform exactly the same commands as it is done for a "usual" ECM manoeuver, the Star Tracker is discarded during the whole manoeuvre (thus the AOCS control loop only relies on the gyro measurements)
(2) Case B: the Star Tracker is discarded only during the slews.

It has been shown that if the STR is discarded during the whole duration of the ECM, the STR does not come back in the AOCS loop at the end of the ECM because the innovation of the Kalman filter is too high after a few days. In that case, the pointing error at the end of the long duration ECM was 33° in simulation A.
For simulation B, the STR measurements can be used in the AOCS control loop except during the time where the STR is blinded when the Earth is in his Field of View. But we confirmed that when the Field of View allows us to track stars again, the innovation is low enough after less than half of the orbit to lock the Kalman filter with the STR again. Therefore, the pointing error between the target attitude and the actual attitude remains low.
The conclusion of these first tests is that Case B is the preferred one: we need to keep the STR during the inertial phase. But this good result of case B has to be taken with caution because the gyro performance in the simulator might not be perfectly representative of gyro performances in real life.
Indeed, as explained earlier, the gyro measurements are used to propagate the different quaternions to further dates. Errors in the gyro measurements can introduce errors in the propagation. The main error sources in gyro measurements are drift and misalignment
In order to conclude on a long duration ECM, more analyses were required from Thales Alenia Space (TAS) from AOCS point of view but also on the different subsystems of the satellite.

7.2 *THALES ALENIA SPACE studies*

7.2.1 *AOCS*

As mentioned just above, the key parameters for AOCS to be simulated are the gyro drifts and misalignments.
TAS gave to CNES a set of parameters, allowing to simulate the gyro behaviour in PRESTO using two options:
1) One with "realistic" gyro drift and misalignment, in order to be as representative of the real satellite as possible
2) One with "robust" gyro drift and misalignment, in order to take margins with respect to the representative option and verify that even in that case, the AOCS is still performing well

Two new simulations made then at CNES with PRESTO simulator showed good performances of the AOCS loop in both cases: after each blind of the STR by the Earth, the innovation was low enough to re-lock the AOCS loop, and the satellite attitude was still well pointing in order to ensure that the arm was still cooling.
In order to strengthen the conclusion, THALES ALENIA SPACE also made some calculations of order of magnitude, and used an AOCS tool called PASIFAE that showed similar results.

7.2.2 *Thermics*

For a Long ECM, we had to study if a thermal FDIR (Failure Detection Isolation and Recovery) could trigger and if the heating power was enough for the Platform.
The idea is to start off with the current temperatures of the Platform in a "NOM" attitude, and then to extrapolate what would be the situation in the "Long ECM" attitude, considering a linear ageing of the thermal performances in the next 10 years.
Actually, we saw that if the arm of the Payload has to be in the Solar plane, two configurations are possible:
Either +Ys is in the direction of the Sun, either –Ys is in the direction of the Sun (Figure 15).

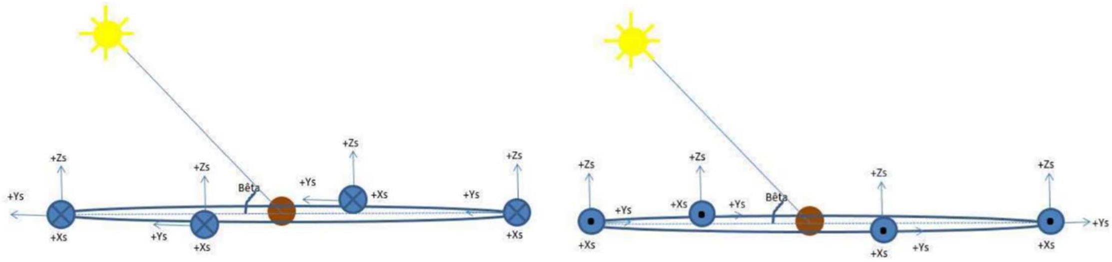


Figure 15. Satellite axes for the two options (*left:* +Ys towards the Sun; *right:* **–**Ys towards the Sun)

The analysis made by THALES ALENIA SPACE showed that if +Ys is in the direction of the Sun, the gyro electronics could reach the FDIR threshold, so that this option is not recommended.
For the **–**Ys option, the temperature of the platform could increase by a maximum of 3°C, which is acceptable, without using more heating power.

7.2.3 *Power*

SMOS uses two solar panels giving a maximum of more than 1 kW. After more than 10 years in orbit, the solar panels have been nominally degraded, as well as the battery capacity.
Then we need to know if the available power would be enough for the Long ECM. The battery capacity is not critical since the Long ECM happens at the beginning and at the end of the eclipse period.
We have just seen that the heating power would not change. For the Payload, ESAC analysed the power needs during the Long ECM.
Assuming Platform and Payload consumptions, and no Power subsystem failure in the next years, the power budget analysis shows that the predicted available power for the Long ECM, is greater than the maximum total need, even in case of 1 string loss and until end of life.

7.3 *CNES add-on studies*

7.3.1 *Moon in the FOV of the STR during the inertial phase*

In theory, if we are unlucky, the Moon could enter the STR Field of View during the inertial phase of the Long ECM. The specification of the STR states the STR is robust to the Moon in the Field of View. But the bad news is that even if the STR still provides attitude determination, the OBSW can discard the STR if it is using less than 6 stars or if the innovation threshold is triggered...
A first idea was to take advantage of the fact that two opposite attitudes are possible for the Long ECM. It means that if the Moon is in the Field of View of the Star Tracker for a first attitude option, another configuration is available! But the bad news came when the thermal expert explained that the option +Ys towards the Sun was no longer possible as explained in the previous chapter... we had to find another solution!
The question was then to determine whether *SMOS* can rely on gyro-only configuration while the STR is discarded because of the Moon. During the Long ECM, the worst-case configuration is as follows: the Moon takes 28 days to perform one orbit around the Earth (360°), hence moving at 12.9° per day. If the Moon is in a very inconvenient place w.r.t the STR field-of-view, by considering a protection angle of 13,5°, it could bother the STR for ~2 days. An analysis has been made by THALES ALENIA SPACE to see if the gyro-only could stand that duration. The conclusion is that we could reach in a worst case 11.2° depointing, which is assessed to be too high for the operation.
Finally, a theoretical study has been performed by CNES to see if the Moon could be in the FOV of the STR during the potential future ECM in November and January. It shows that with a 13.5° protection angle, there would be no problem at least for the next 10 years (Figure 16).

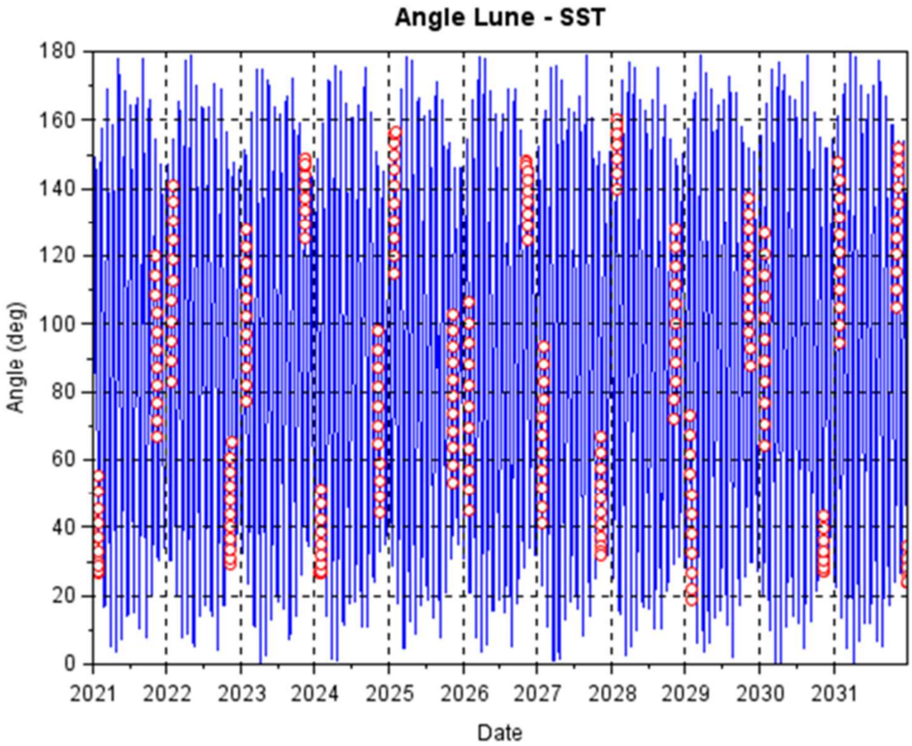


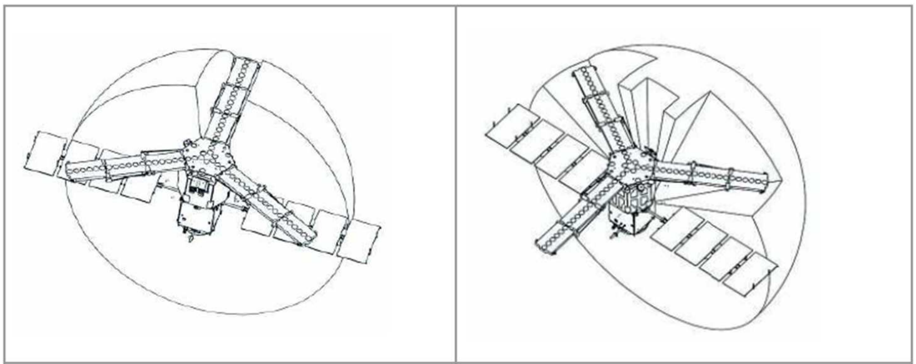
Figure 16. Protection angle between the STR and the Moon, considering an inertial attitude as defined for a *Long ECM*. Red dots correspond to November and January potential *Long ECM*: all red dots are above the 13.5° threshold

7.3.2 *GPS Satellites visibility*

The GPS receiver is connected to two antennas, and one of the two is always facing the opposite of the Earth. But because of the inertial attitude of the Long ECM, the number of GPS satellites in visibility will decrease.
An analysis has been made to show that the two FDIR used to monitor the GPS receiver should not trigger in nominal situations.
But we observe for a few years a degradation of the GPS availability, probably due to jamming over Mid-Est. If this jamming increases with years, there could be a risk to trigger one of the FDIR and to transition the satellite in a degraded mode (REDUCED mode, which means the GPS is no longer in the time loop). In that case, since there is no important time accuracy needs (no mission in progress), the idea is to stay in this REDUCED mode, and upload a time offset during open hours/working days (the on-board oscillator drifts of a few seconds per day) and go back to CC NOMINAL mode after the end of the Long ECM.

7.3.3 *TMTC Link*

In nominal pointing, the two *S* band antennas are masked by the arms (Figure 17).



+Zs TT&C LHCP Antenna	-Zs TT&C RHCP Antenna

Figure 17. *SMOS* payload mask for the *S* band antennas

Before launch, a specific analysis has been made to see if the satellite could face some link interruptions because of the arms of the payload that decreases the Signal to Noise Ratio. With respect to these analyses made before launch, we now use only MUM ground antennas with much higher gains. And also, during the ECM, the position of the *S* band antennas is different wrt the arms leading to the fact that half of the orbit will be more favourable since we would have no masking. Finally, an analysis has been made by an RF expert and confirms we will have no TMTC problem. Regarding the polarisation, it should not really change between a nominal pointing and an ECM pointing, since the antennas are on +Z and –Zs walls, and an ECM is a rotation around the Z axis. The files generated to set the polarisation used (right or left) are independent from the attitude.

7.3.4 *Risk Mitigation Maneuver (RMM) during Long ECM*

Once the long ECM is agreed and demonstrated feasible, a new issue arises. A collision risk can appear after *SMOS* has started its inertial pointing phase. The Article 7 of the French Space Act enforces satellite operators to prevent, as much as possible, any collision in orbit. The long ECM is a controlled phase, hence declaring *SMOS* a non-maneuverable object during such operation is not possible. For this reason, the CNES must be able to perform a risk mitigation manoeuvre at any moment in the inertial pointing.

The Flight Dynamic Software, also known as G2, is the core element that computes orbit manoeuvres and attitude guidance. However, an ECM usually lasts for only tens of minutes, thus, there is no reason to interrupt it in regular operations. Actually, the software is not even designed to abort such guidance; it is only able to remove it entirely. Trying to cancel an ongoing long ECM with regular collision risk management procedure results in a strong satellite-ground inconsistency leading to a fall into Safe Mode before any orbital manoeuvre can be performed. Unfortunately, the software is also too old and critical to ask for any evolution.

The Operational Flight Dynamic Team addressed the issue by elaborating different ways to perform a risk mitigation manoeuvre in long ECM. As an example, a solution implied to change the generation of the ECM guidance itself: instead of creating one long inertial guidance, several smaller ones could be created. In that way, *SMOS* reaches nominal guidance multiple times which gives opportunities to cancel the remainder of the inertial phase properly and execute an orbit manoeuvre. This solution was not approved; it requires too many manual and error-prompt actions to create a relevant chain of smaller ECM to address every thermal, attitude control, collision risk management and chronology problems.

Finally, a trade-off between satellite safety and operability left one solution to realise the risk mitigation manoeuvre. It consists in a manual overwrite of the G2 commands in order to bring *SMOS* into a nominal pointing mode and then perform the orbit manoeuvre. Even though the satellite-ground consistency is broken, the resulting attitude error in the commands remains handled by *SMOS*' Flight Software. A worst-case simulation on PRESTO simulator proved the procedure successful (Figure 18). Moreover, the observed attitude error was close enough to the expected value to show it is understood and mastered.

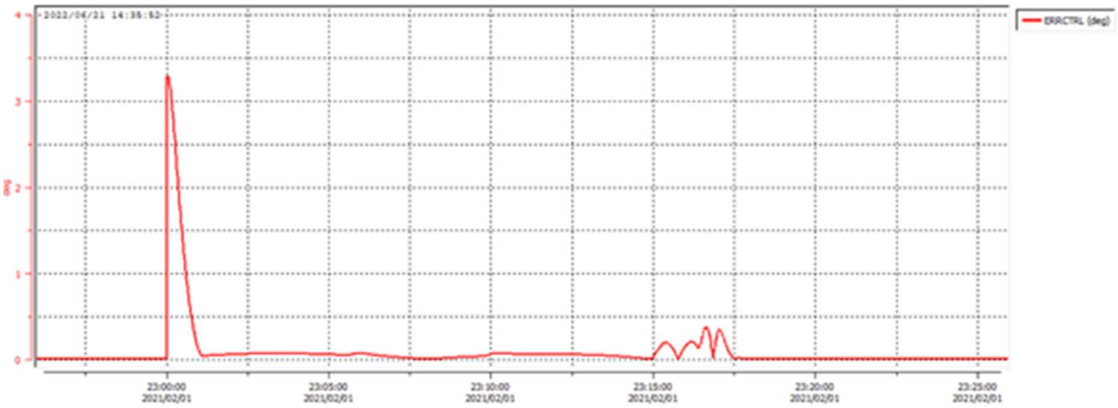


Figure 18. PRESTO, worst-case, *Long ECM* abort test: attitude error telemetry (degrees). The inertial pointing, manual interruption, occurs 01 FEB 2022 23:00:00. Nominal guidance is restored at 23:17:30

This new risk mitigation procedure not only allows achieving an orbit manoeuvre in a long ECM, it also grants *SMOS* to be back in inertial, thermally safe, pointing before the ARM-A reaches hazardous temperatures. Every aspect of this late issue is then coped with, and the whole long ECM operation can be approved. Flight Dynamics procedures were updated with this method and members of the team now train to be able to execute it when it will be necessary.

7.3.5 *Sequence Plan*

Finally, after all the studies, we are very confident of the feasibility of the Long ECM.
The point is that the first Long ECM could be done in maybe 5 or 10 years, meaning that we could forget how to proceed! Also, the people who analysed this Long ECM might change jobs, that is why we thought it was a priority to sum-up all the activities to be done before, during and after the Long ECM in a document.
To do so, CNES wrote together with ESA FOS a document named "Long ECM Sequence Plan" or SPL, to describe:

- The criteria to decide if we need to perform a Long ECM
- The different files to be used to compute the Long ECM
- All checks to be done (gyro performances assessment, temperatures) before the Long ECM
- The trainings of the Flight Control Team to do before in case of contingency or a RMM
- The management of the *S* band passes booking
- The expected alarms

8. **Conclusions**

We have introduced the *SMOS* mission for Earth observation, described its platform and single instrument concept (MIRAS), and its joint operation by CNES and ESA. Further we analysed the thermal anomaly that occurred in 2015, affecting the duty cycle of segment A1 of the MIRAS antenna, as well as an array of potential mitigation scenarios.
These scenarios were assessed, and an optimal solution selected. At the end of the process, CNES and ESA teams, with support from industry partners, have demonstrated readiness to protect the payload during critical, temperature-rising periods. We have not yet executed the so-called "*Long ECM*" manoeuvre, but are now fully prepared should the need arise.
The major issue we have faced with this anomaly was the fact that expertise was not readily available, as it had by now moved to other projects or even retired. Teams had to re-learn how to utilise tools and understand, with an elevated level of detail, the rationale of the design behind the system as a whole. In addition, modifying the ground segment software was prohibitively impossible. That is why we solved the challenge by employing an already existing manoeuvre (i.e., ECM) and altered it to answer the problem.
The rapid and agile development of ad hoc payload thermal and downlink models (unavailable when we first came to face the new anomaly) allowed the operational teams to accurately simulate various scenarios. And thus, we were able to select the most suitable set-up and attitudes discarding the ones not fulfilling the operational and payload safety requirements. These developments necessitated strong adaptability from all the teams and showcased the excellent

cooperation between the two space agencies. The will to reach a common goal substantially contributed to the success of the study and is permitting for a maximal mission extension to be considered. The scientific community has become appreciative of these efforts, as *SMOS* data are being used worldwide very successfully, and no follow-up mission is currently foreseen.

Acknowledgements
Authors warmly thank Klaus Scipal, *SMOS* ESA Mission Manager, for the coordination of the Working Group, as well as the teams at ESA PLSO and AIRBUS Spain for their technical support. CNES SOGS thanks Alain Lamy, Maxime Thierry, and Arthur Fezard for simulations and analysis. JMCC thanks V. Rodríguez González (Telespazio Vega UK) and E. Uranga Sáez (ISDEFE) for insightful discussion, and gratefully acknowledges ISDEFE for financial support.