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SmallSats: when real life operations exceed expectations

Pierre Serra[a]*, Claudia Ciocirlan[b], Mathias Zaroubian[c], Audric Baron[d], Frederick Viaud[e]

[a] *Centre National d'Etudes Spatiales (CNES), France, Pierre.Serra@cnes.fr*
[b] *Centre National d'Etudes Spatiales (CNES), France, Claudia.Ciocirlan@cnes.fr*
[c] *Centre National d'Etudes Spatiales (CNES), France, Mathias.Zaroubian@cnes.fr*
[d] *Centre National d'Etudes Spatiales (CNES), France, Audric.Baron@cnes.fr*
[e] *Centre National d'Etudes Spatiales (CNES), France, Frederick.Viaud@cnes.fr*
* Corresponding Author

Abstract

When you first hear about SmallSats you can often think "small": low cost project, no expertise, reduced teams, few on board procedures, operations performed in a spooky basement… But it is not always that simple nor spooky and it can even be the occasion of thrilling and challenging operations. Indeed, most of the time, such satellites have no redundancy onboard, less shielding due to the lack of room and embark non-spatialized hardware that make equipment more sensitive to SEU (Single Event Upsets) in orbit. As a result, the operational teams may face a variety of anomalies and have to manage it with means at hand. In that case, it is better if they can rely on a control center with enough automation capabilities and ensuring rapid testing facilities. Over the past 20 years, more and more SmallSats have been developed and operated by all kind of space actors, from universities to national space agencies including CNES. And for one recent case, we had to deal with several significant anomalies requiring urgent intervention.

Thanks to a very important knowledge in concept of operations and automations at CNES, we managed to put together a control center built for large traditional satellites and our processes adapted to small ones. During the integration and the testing phases we imagined several ways of using our tools and we tried to anticipate the nominal and contingency operations that could occur. We also built strong relationships between all the teams: operations, experts, satellite manufacturers and the project. The result led to successful Launch and Early Operations Phase and commissioning phase. But the most exciting part was yet to come: during the next first months of exploitation, we discovered several behaviours that were not experienced on ground, exactly like we did on our more conventional Spacecraft, but with more significant impact on the mission. First, the single GNSS started to malfunction due to SEU. Then, unpredictable internal monitoring began to trig and to turn off the reaction wheels. Without our intervention, the mission would be often interrupted and the satellite could sometimes end up in survival mode.

What is remarkable here is the way behaviours were observed and the solutions that were implemented. We have managed to mix together the possibilities already present onboard, especially via the Packet Utilisation Standard, and the automatisms on ground. Applying different ground operations based on the telemetry and changing the onboard configuration, we succeeded in keeping the satellite in nominal mode and continuing the mission. And most of all, these solutions were successfully tested and implemented in a few days thanks to the coordination and involvement of all.

This paper will present the way the operators and the experts adapted the procedures in order to cope with the satellite behaviour in space and to keep the mission going without interruptions as much as possible. All this in the context of SmallSats operations, with no on call operators or controllers available onsite outside the working hours but with substantial effort and time though.

Keywords: Operations, SmallSat, automation, cubesat, anomaly, ISIS

Acronyms/Abbreviations

ADS	Airbus Defence and Space
CALIPSO	Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations satellite
CCC	Command and Control Centre
CNES	National Centre for Space Studies – Centre National d'Etudes Spatiales
DAISY	Data Archive for Investigation and SYnthesis
FCP	Flight Control Procedure
FDTM	Failure Diagnosis Telemetry

GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
ISIS	Initiative for Space Innovative Standard
LEOP	Launch and Early Orbit Phase
PMON	Parameter Monitoring
PUS	Packet Utilisation Standard
PVT	Position, Velocity, Time
RW	Reaction Wheel
SEU	Single-Event Upset
SMOS	Soil Moisture and Ocean Salinity satellite
SOO	Sequence Of Operations
SWOT	Surface Water and Ocean Topography satellite
TAS	Thales Alenia Space
TC	Telecommand
TM	Telemetry
VIMA	Visualisation Main Application

1. Introduction

At the beginning of a SmallSat mission, the same contingencies than usual have to be contemplated but their management has to make do with "new space" constraints such as: limited platform architecture in terms of redundancy, low ratio in human resources, in some cases lower mission availability requirements, or no on-call operators. It is known that the equipment is more fragile and sensitive to space environment and that the limited validation on ground would miss out on some errors or malfunction. The operations have to rely on a Command and Control Centre (CCC) able to meet the needs and constraints of such mission.

CNES has developed a generic spacecraft operations Control Center Product Line, called the ISIS (Initiative for Space Innovative Standard) Product Line. This Product Line comes with an operational context that is used for several types of missions [1]. In the scope of this paper, the ISIS Product Line is used by SmallSats and is adapted to "new space" missions and classical bigger ones as well.

At CNES, we have already operated several SmallSats but the one described in this paper is the first one using an ISIS CCC. This new generation of CCC enabled us to redesign the way we are doing the operations, particularly in the case of a SmallSat. Despite our preparation before launch, we have face many unexpected anomalies and failures that forced us to adapt. We had to think about efficient and simple solutions to make the spacecraft continue its mission.

In section 2, this paper starts with a presentation of the context of our SmallSat project. It describes the ISIS CCC, the operational teams' organisation and the platform architecture of the spacecraft and its constraints. Then, section 3 presents three types of major anomalies that we have faced and the workarounds we have put in place to overcome them. Finally, section 4 is about the way we managed other unexpected anomalies and activities and how we have automated the routine operations to relieve the operational teams.

2. Context

2.1 ISIS Command and Control Centre

In the early 2010, the aim of CNES, French Space Agency, was to improve its spacecraft operations control system. In the frame of a project called ISIS "Initiative for Space Innovative Standards", created in partnership with two major European prime contractors: Thales Alenia Space (TAS) and Airbus Defense and Space (ADS), a new Ground Control Center product line was developed in order to be used by all the future missions operated by the CNES. The Product line was not only defined as a set of software working together, but also as a framework for a strong operational concept, to be used by different missions. The scope is to have the same tools, design, automation, planning and routine operations for every single mission including all possible configuration from a single 2 tones satellite to a constellation 4kg Cubesats. This is why operations for Small Satellites at CNES inherit from a strong operational concepts knowledge.

Since 2021, the new ISIS CCC is used for the LEOP, commissioning, routine, contingency and post-mission disposal operations of more and more satellites, regardless of their size and complexity. Every future spacecraft is expected to be operated from this kind of CCC.

This adaptability and extensibility to different missions were among the main objectives of ISIS product line. It implements the Packet Utilisation Standard (PUS) on ground and offers a modularity to fit missions' needs thanks to a service oriented architecture. Thus, all ground activities are based on the same tools, provide identical functionality and follow the same processes depending the requirements. This enables us to standardise our way of doing the operations and to capitalise on the experience of each mission. In this way, even SmallSats can benefit from the advantage of a technically advanced CCC used for the largest missions. It also enables the teams to operate several ISIS based missions at the same time, because the work environment, methods and tools are similar on each of them. It simplifies and speeds up the training, which reduces the operations' cost.

Two important concepts of ISIS are worth keeping in mind to understand how the operations described in this paper were made.
Firstly, an ISIS CCC is able to process telemetry (TM) parameters and to store it as Time Based Data [2]. Then operational teams can use it within procedures to perform checks and conditions according to the parameters' value. These parameters can also be monitored and raise ground alarms or be automatically computed by ground computed parameters, which can themselves be used afterwards or monitored.
Secondly, ISIS provides an advanced automation process. Through automation rules and Groups Of Operations, The Sequence Of Operations (SOO) makes it possible to organize every activity for days without human intervention [3]. The scheduled operations managed by the SOO may vary depending on the value of a TM parameter or on the result of a low level procedure.

2.2 Operational team organisation

At CNES, the high level organisation of operational teams is mostly the same between SmallSats and large satellites. Within an ISIS Command and Control Centre, the Spacecraft Operations Manager coordinates the activities of the Flight Control Team, the Ground Control Team, the Flight Dynamics Team and the Operators to prepare and to conduct the operations (Figure 1). When necessary, the operational teams can rely on experts of each satellite subsystem (GNC, Electrical and Power System, Radio Frequency, Payload) for analyses and on simulators to test the activities before their execution on board. The CCC and the Mission Centre are working in close collaboration to produce the mission plans for the payload and to execute them.

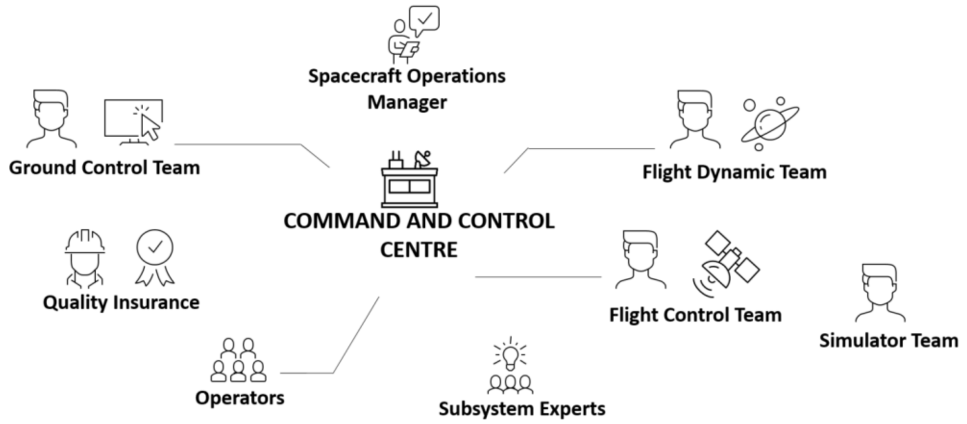


Figure 1:CNES' typical organisation of operational teams in an ISIS CCC

Nevertheless, unlike other big conventional satellites operated at CNES, SmallSats have to deal with several specific constraints that impact the operations organisation and the project management on ground.
First, the size of the different teams is reduced to meet budget constraints. Most of the time, there is a minimum of only 1 person present on site in each team and this person is responsible to all the operations and ancillary activities (routine, contingencies, analysis, coordination meetings, tests) and sometimes for other missions at the same time.
There is no on-call duty service as there is no on-board propulsion system and no need to manage collision risk. So all the operations are done during working hours and working days.
Mission's priority is generally lower than for larger satellites, so in case of anomalies requiring intervention of the operational teams on several satellites the SmallSat will come last. In addition, if there is a conflict on booked passes with another big satellite, it is the SmallSat that will give the priority to the other one.
Finally, considering the above constraints, all the SmallSat's project members accept to take more risk than for more conventional missions, to carry out the operations at reduced cost and in a limited time.

2.3 SmallSat overview

2.3.1 Platform architecture and constraints

Several SmallSats are being operated at CNES, all of them with their own specific platform and central software. Nevertheless, one can define a generic architecture and a common set of principles that can apply to all of them. The following statements describe the typical SmallSat on which we performed the operations described in this paper.
We assume that the platform has limited capabilities, with no propulsion system and is composed of:

- Battery
- Solar panels
- Solar sensors
- Magnetic torquer
- Magnetometer
- 1 GNSS, used in nominal mode only
- 4 Reaction Wheels (RW), used in nominal mode only

There are two satellite modes: the nominal mode and the survival mode. Depending on the situation, a transition from nominal to survival mode can occur with a complete reboot of the satellite central software or not. In both cases, the satellite reconfigures itself to keep ON only the necessary equipment to ensure the safety of the platform.

The conception and development of spacecraft followed a Design-To-Cost approach so there is no redundant equipment and a limited number of monitoring on board. The satellite's central software and its equipment are sensitive to Single Event Upsets (SEU). Due the satellite' limitation, a mission analysis had to be done to optimise the utilisation of the X band, power consuming, regarding the battery and the payload. It has a simplified Command & Control system, compliant with existing standards such as the PUS but without all services or subservices, that reduces the possibilities of actions. Thus, only services 5 (event reporting service), 19 (event action service) and 12 (on board monitoring service), as described in ECSS standard [4], are implemented in the spacecraft central software regarding the Fault detection, isolation, and recovery (FDIR) management.

2.3.2 Unexpected behaviours

The validation of the SmallSat platform was not as exhaustive as on bigger classical spacecraft, especially as the mission has initially be designed for only one year. The equipment is more fragile and as said above there are many platform constraints. The project team agreed to take that risk but, as a consequence, the real life operations have been much more animated than usual. For example, the first year of operations, there were **23 transitions to survival mode**. Comparatively, there was no switch to survival mode on SWOT satellite (launch in December 2022) and only 2 on CALIPSO (17.5-year service life) and SMOS (15-year service life) satellites operated by CNES. This added a significant workload on the operational teams that was designed for "small" operations.

Among the equipment, the GNSS and the RW turned out to be the weakest links of our SmallSat. They were the cause of most of the satellite reboots, especially the RW which have cause 12 reboots. But the operational teams have done their best to manage these contingencies and to automate as much as possible the recovery procedures, as detailed in next section 3.
8 transitions to survival mode have also been attributed to SEU damaging the satellite central software and provoking a reboot. In these cases, we only had few information about the reason of the reboots and the SEU were the more likely hypothesis, especially when the SmallSat was in the South Atlantic Anomaly area or near the poles.

Furthermore, there were regularly other "minor" anomalies on board impacting all the equipment, but not important enough to trigger on-board monitoring. The operational teams have put in place several ground monitoring and automated periodic checks in the ISIS CCC to simplify the supervision of the SmallSat status, which is described in section 4.

3. Major anomalies and their automated workaround

3.1 Transition to survival mode

3.1.1 Anomaly description

There are many reasons why a satellite can switch from its nominal mode to its survival mode. Especially for our SmallSat that is sensitive to SEU, with no redundant equipment and with a short life time. When this happens, the operational teams want to access the TM quickly to analyse it, to understand the reason of the transition and to check the status of the satellite.

It is important to note that in case of a satellite reboot, one particular packet store, the Failure Diagnosis TM (FDTM) packet store, freezes and its status switches to DISABLED. This packet store contains the recorded TM of the last few minutes before the reboot, which may be useful during investigation. The Flight Control Team has to enable this packet store after its download to the ground and as soon as possible in case of another anomaly.

The SmallSat presented in this paper had face several reboots with switches from nominal to survival mode, mostly due to SEU at the beginning of life and later because of failure on equipment as described in subsections 3.2 and 3.3. It is crucial to detect these transitions and to perform as soon as possible some first-line activities to make data available to the Flight Control Team that will perform the first post reboot analyses.

3.1.2 First-line automated step

At CNES, every mission has to anticipate before launch the management of survival mode transition and those using ISIS work in quite the same way. At the beginning of every pass, there is a Flight Control Procedure (FCP) named PASS_INIT_CHECKS.fcp whose role is to check if TM is received on ground by the CCC and if TC connection link is established. But this procedure also checks if there has been a reboot of the satellite, from the Nominal mode or from the survival mode itself too. To do so, the FCP gets the current status (ENABLED or DISABLED) of the FDTM packet store, and compare it to its previous value that has been retrieved during previous pass and stored in an operation parameter in the CCC. If the FDTM packet store is DISABLED and was previously ENABLED, then that means that a transition occurred. When this condition is filled, the FCP automatically executes first-line recovery activities like the downlink of the TM stored in the FDTM packet store and the dump of some TM reports with information about the reason of the last reboot. At the end, the FCP stops the execution of next planned activities, waiting for the operational teams to take action. This automated sequence is illustrated in the Figure 2 below.
If there is no TM detected, then the FCP aborts and stops the automated execution of next planned activities. And if TM is well received by the CCC but no reboot detected, then the FCP simply ends.

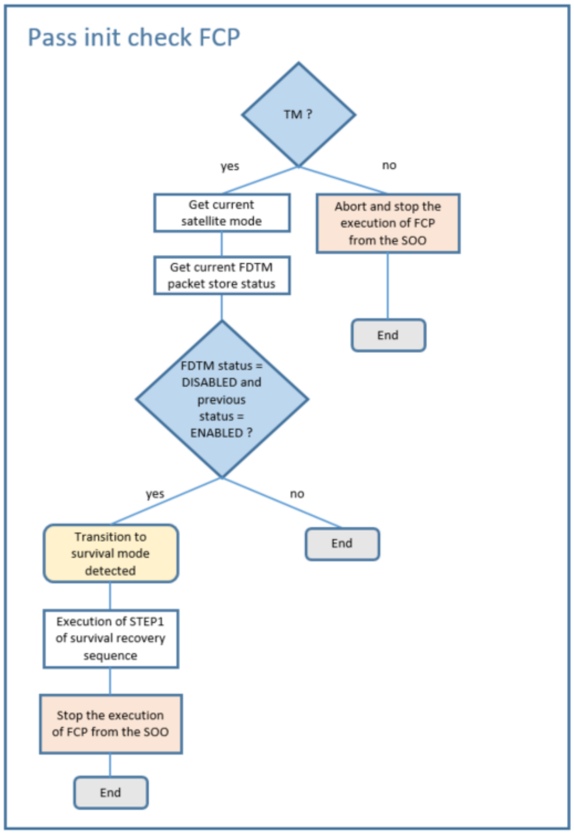


Figure 2: initial logical sequence of PASS_INIT_CHECKS FCP

Even if this automated workaround is not specific to our SmallSat and is implemented for much bigger satellites, it has been used a lot by it. And for the next anomalies described below, the other workarounds are based on the PASS_INIT_CHECKS FCP also.

3.2 Unexpected GNSS switch off

3.2.1 Anomaly description

The first major anomaly that urged us to introduce a new automated workaround concerns the GNSS receiver of our SmallSat. This equipment is sensitive to radiative phenomenon since it was not specially designed for space applications, causing some malfunction including one that led to a satellite reboot and switch to survival mode.

The TM analyses of the routine phase showed that the GNSS stops emitting a valid PVT about 6 times a day, for a period of less than 20 minutes at a time, before starting again. This has usually no consequences, as during these periods of invalidity the Guidance Navigation and Control (GNC) software of the spacecraft propagates the last valid PVT received from the GNSS to determine its position and to control its attitude. Sometimes, the invalidity lasts longer, an on-board alarm triggers and an event of the PUS service 5 is emitted. In that case, the Flight Control Team has to execute a contingency procedure to reboot the GNSS, which fixes the anomaly and enables the equipment to emit a valid PVT again.

But on the evening of the 12th of January 2024, the PVT validity flag froze at the NOT_VALID value and an on-board alarm triggered. As it was on a Friday and as there is no on call service for this SmallSat, the operational teams could not see this problem until Monday. To make things worse, the last PVT transmitted to the GNC software was ultimately not precise at all, even if its PVT flag was valid (due to a too loose validity evaluation filtering by the central software). So the initial PVT on which the propagation was based was wrong and as a consequence the satellite battery started to discharge because the satellite pointing was wrong. The situation deteriorated over time, leading finally 2 days later, on the 14th of January, to a satellite reboot due to a battery discharge of 60% as shown in Figure 3.

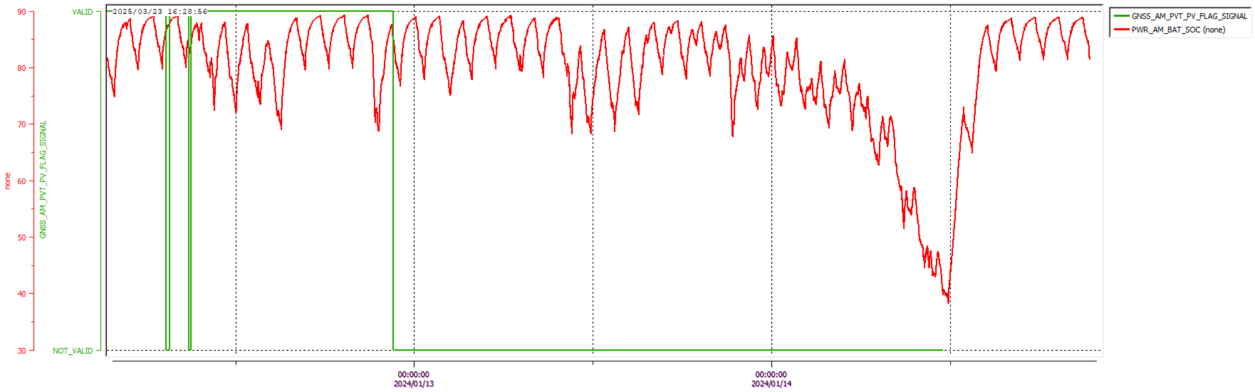


Figure 3: battery State Of Charge and PVT valid flag evolution

3.2.2 Automated workaround

After investigation and understanding of the situation, the operational teams thought about a way to switch back on the emission of a valid PVT from the GNSS, before such a deep discharge. The solution had to be fully automated to cover times when there are no people on site, like in the example above. Thus, a two-part workaround has been developed to automatically reboot the GNSS after a too long period without a valid PVT. It is represented in next *Figure 4*.

On board side, a new event action has been configured using the PUS service 19 sub-service 1, in order to switch off the GNSS when the service 5 event linked to a long PVT invalidity period is emitted on board. When this event raises, the TC to switch off the GNSS is sent. As there is no more complex PUS service available on board, like the service 18 (on-board control procedure service) or 21 (telecommand sequencing service), we could only configure one single

TC with service 19. So we had to find something else to send the other TC needed to switch the GNSS on after that, as described below.

On ground side, an automated switch on of the GNSS made by the CCC has been implemented to complete the reboot. We have modified the PASS_INIT_CHECKS FCP, which is already automatically executed by the SOO at the beginning of every pass. We added an additional check of the GNSS state which switches on the GNSS if it is OFF and if the satellite is still in Nominal mode. In this FCP, we are not constrained to one single TC and we can send all the necessary TC needed to switch on the equipment. The implementation of the workaround inside the PASS_INIT_CHECKS FCP is illustrated in **Appendix A**.

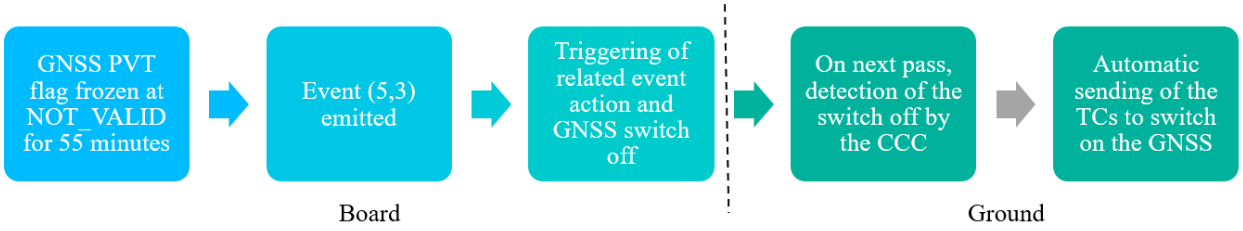


Figure 4: automated board and ground steps of the GNSS workaround

During the 1-year period following the implementation of the workaround, it triggered 6 times as shown in the Table 1 below, 3 of them when no operational team was there (weekend or Christmas holidays). So it fulfilled its role perfectly.

Date	16/02/2024	28/03/2024	10/08/2024	25/08/2024	05/09/2024	24/12/2024

Table 1: triggering dates of the GNSS workaround

3.3 Friction and deterioration of the RW

3.3.1 Anomaly description

The second time we had to automate a workaround was when the reaction wheels of our SmallSat started to malfunction seriously. After the initially agreed first year, a mission extension was decided, acknowledging the risks involved regarding the qualification areas of the equipment, particularly the wheels.
From June 2024, two of the four RW started to face friction due to wear and tear on equipment. Regularly, the current consumption of these wheels increased and sometimes to the point where an internal monitoring of the equipment triggered. At the end, this anomaly led to many switches to satellite survival mode, as explained below.

When this happens, a fault state flag rises up in TM and the wheel in difficulty starts ignoring the speed commands sent by the GNC software of the central software. As illustrated in Figure 5, the wheel 'speed falls to 0 rad/sec and after 100 seconds, a parameter monitoring (PMON) of the PUS service 12 triggers and switches the wheel off. It because the speed measure falls to a frozen value that this monitoring triggers.
When a single wheel encounters a fault, the satellite is capable of autonomously reconfiguring itself to operate nominally with 3 wheels instead of 4. However, in the case where 2 wheels are simultaneously affected, this leads to a reboot and return to survival mode. Things only got worse as this failure began to occur very often on two wheels (3 and 4), leading to several switches to survival mode on the 2nd, 6th and 9th of July. It had a serious impact on the mission which was only possible in Nominal mode. The operational teams were also very involved each time to do the analyses and to execute the recovery procedures to Nominal mode. A sustainable solution had to be found to continue the mission and to release the pressure on the teams.

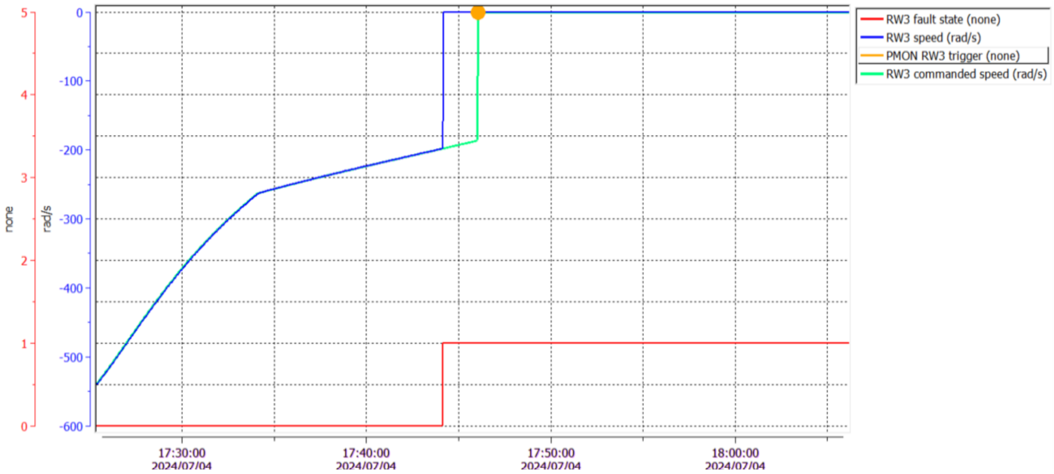


Figure 5: RW3 speed vs commanded speed and fault state flag evolution before PMON triggering

3.3.2 Automated ground-board workaround

First, a partial workaround has been put in place to reduce the occurrences of the SmallSat reboots. Inspired by what we had previously done for the GNSS, we automated on ground the restart of the failed RW through an additional check performed inside the PASS_INIT_CHECKS FCP. If a RW is detected OFF, then the switch on is automatically executed. Contrary to the GNSS workaround, we did not need to implement something new on board because the RW switch OFF was already made by the central software in case of frozen measures on a RW. The implementation of the workaround inside the PASS_INIT_CHECKS FCP is illustrated in **Appendix A**.

This workaround was applied on the 11th of July 2024 and it triggered 21 times between this date and the end of November. It has restarted 16 times the RW3 and 5 times the RW4.

Unfortunately, that did not prevent completely the switches to survival mode from occurring and by two times the RW 3 and 4 failed together. Indeed, the shortcoming of this solution is that the restart of a failed RW depends on the next pass, during which a FCP detects the failure and execute the switch on. Waiting for this pass after the failure, the SmallSat is vulnerable to second RW breakdown that would lead to a reboot in survival mode, especially if it is planned in a long time. A more complete workaround had to be found.

3.3.3 Automated board workaround

During the numerous tests that have been made to analyse the wheels behaviour, we found that it was possible to make the wheel quit its default state and follow the speed commands again, by sending a certain type of IDLE TC to the equipment. Based on that and after careful consideration with all members of the operational teams and the SmallSat's manufacturer, we get to the following solution.

Four new monitoring of PUS service 12 were added on board, which watch for each RW's fault state parameter. If it takes the value 1 then an event of PUS service 5 is emitted. And three new event actions of PUS service 19 were configured to send an IDLE TC to the failed wheel, for wheel 3 et 4. The aim was to put the wheel back to the GNC loop before the 100sec delay at the end of which the PMON for frozen measure triggers. A new version of the central software was needed to implement the new monitoring, as the SmallSat did not have the PUS service 12 subservice 5 to add new PMON on-board.

After development of the software by the spacecraft manufacturer, the operational team carried out its upload on board on the 25th of November 2024. It triggered 74 times between this date and the end of December with 11 times for the RW3 and 63 times for the RW4.

Unfortunately, by the end of December 2024 this fault state anomaly disappeared and the wheels started to stop running without fault state, due to an increase of the friction. Then the PMON for frozen measure applied again and the workaround became useless because the wheel did not stop with a fault state condition, as illustrated in Figure 6 below. The ground-board workaround, with the automated switch on of the failed RW, could still cover this situation but only

partially as explained before (subsection 3.3.2). It impacted the possibility to do the mission in a significant way now and compromised the future operations of our SmallSat.
But this 2nd workaround had enabled the SmallSat to continue its mission for 1 more month in December 2024, so it proved to be quite efficient.

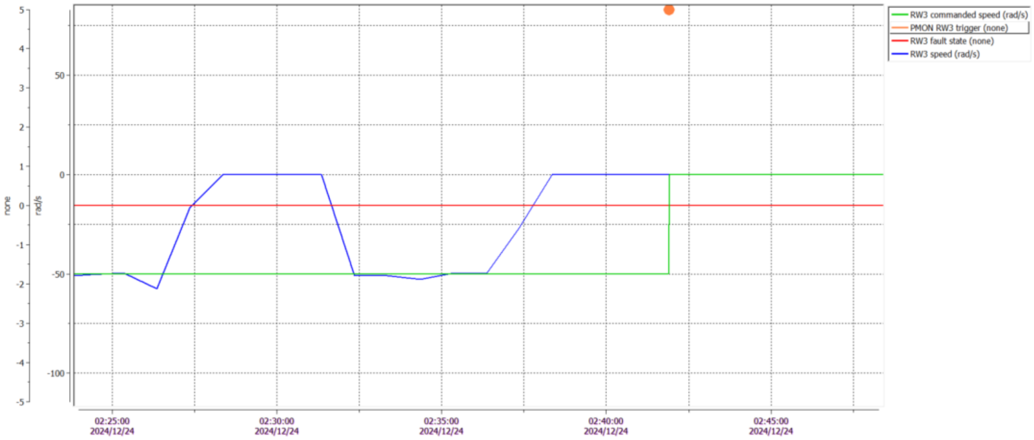


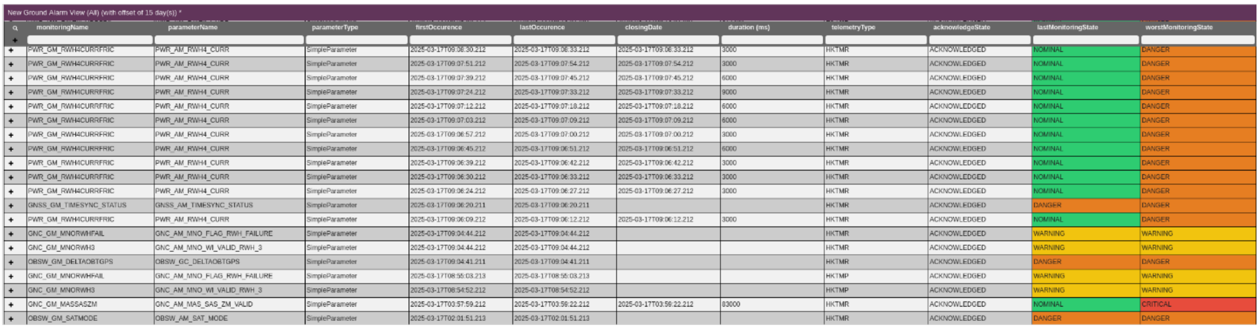
Figure 6: RW3 speed vs commanded speed and fault state flag evolution before PMON triggering

4. Dealing with ever more day-to-day operations

To help the supervision of the SmallSat during all the phases of operations and to reduce the ever increasing workload on the operational teams, we used the power of the ISIS CCC which was designed for bigger satellites as well. We could put in place automatic periodic activities and ground monitoring to warn the operational teams if needed. We also benefited from the complex CCC's tools developed by previous missions to perform exceptional activities such as a software upload from ground.

4.1 Ground monitoring

The Flight Control Team with the help of the Ground Control Team has implemented in the CCC a number of ground monitoring defined by the different subsystem experts. Just like on-board monitoring, it watches over a TM parameter and triggers when it passes below or under a threshold, or when it becomes different from an expected value. It is configured in such a way that it is complementary to on-board monitoring of the PUS service 5, with possible triggering before a real on-board alarm. Each monitoring has a level indicating how critical it is: WARNING (low level), DANGER (medium level) and CRITICAL (high level). For missions with on-call service, only the DANGER and CRITICAL alarms can make a call and only the CRITICAL ones outside the working hours.
On our SmallSat mission, we had implemented 254 ground monitoring, for 2000 on-board parameters, which is only two times lower than on SWOT mission (493 ground monitoring for about 34000 on-board parameters) even if SWOT satellite is 50 times bigger. In space, size is not everything and even a SmallSat has some amount of important TM to monitor to ensure its safety. And we created 69 ground computed parameters whereas there were 254 on SWOT.
With an ISIS CCC we can visualise the triggered on-board or ground monitoring through the VIMA software where all the necessary data to the investigation is available. An example of the VIMA ground monitoring view is visible on Figure 7 below.



New Ground Alarm View (All) (with offset of 15 day(s)) *

	monitoringName	parameterName	parameterType	firstOccurence	lastOccurence	closingDate	duration (ms)	telemetryType	acknowledgeState	lastMonitoringState	worstMonitoringState
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:08:30.212	2025-03-17T09:08:33.212	2025-03-17T09:08:33.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:07:51.212	2025-03-17T09:07:54.212	2025-03-17T09:07:54.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:07:39.212	2025-03-17T09:07:45.212	2025-03-17T09:07:45.212	6000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:07:24.212	2025-03-17T09:07:33.212	2025-03-17T09:07:33.212	9000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:07:12.212	2025-03-17T09:07:18.212	2025-03-17T09:07:18.212	6000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:07:03.212	2025-03-17T09:07:09.212	2025-03-17T09:07:09.212	6000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:57.212	2025-03-17T09:07:00.212	2025-03-17T09:07:00.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:45.212	2025-03-17T09:06:51.212	2025-03-17T09:06:51.212	6000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:39.212	2025-03-17T09:06:42.212	2025-03-17T09:06:42.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:30.212	2025-03-17T09:06:33.212	2025-03-17T09:06:33.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:24.212	2025-03-17T09:06:27.212	2025-03-17T09:06:27.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	GNSS_GM_TIMESYNC_STATUS	GNSS_AM_TIMESYNC_STATUS	SimpleParameter	2025-03-17T09:06:20.211	2025-03-17T09:06:20.211			HKTMR	ACKNOWLEDGED	DANGER	DANGER
+	PWR_GM_RWH4CURRFRIC	PWR_AM_RWH4_CURR	SimpleParameter	2025-03-17T09:06:09.212	2025-03-17T09:06:12.212	2025-03-17T09:06:12.212	3000	HKTMR	ACKNOWLEDGED	NOMINAL	DANGER
+	GNC_GM_MNORWHFAIL	GNC_AM_MNO_FLAG_RWH_FAILURE	SimpleParameter	2025-03-17T09:04:44.212	2025-03-17T09:04:44.212			HKTMR	ACKNOWLEDGED	WARNING	WARNING
+	GNC_GM_MNORWH3	GNC_AM_MNO_WI_VALID_RWH_3	SimpleParameter	2025-03-17T09:04:44.212	2025-03-17T09:04:44.212			HKTMR	ACKNOWLEDGED	WARNING	WARNING
+	OBSW_GM_DELTAOBTGPS	OBSW_GC_DELTAOBTGPS	SimpleParameter	2025-03-17T09:04:41.211	2025-03-17T09:04:41.211			HKTMR	ACKNOWLEDGED	DANGER	DANGER
+	GNC_GM_MNORWHFAIL	GNC_AM_MNO_FLAG_RWH_FAILURE	SimpleParameter	2025-03-17T08:55:03.213	2025-03-17T08:55:03.213			HKTMP	ACKNOWLEDGED	WARNING	WARNING
+	GNC_GM_MNORWH3	GNC_AM_MNO_WI_VALID_RWH_3	SimpleParameter	2025-03-17T08:54:52.212	2025-03-17T08:54:52.212			HKTMP	ACKNOWLEDGED	WARNING	WARNING
+	GNC_GM_MASSASZM	GNC_AM_MAS_SAS_ZM_VALID	SimpleParameter	2025-03-17T03:57:59.212	2025-03-17T03:59:22.212	2025-03-17T03:59:22.212	83000	HKTMR	ACKNOWLEDGED	NOMINAL	CRITICAL
+	OBSW_GM_SATMODE	OBSW_AM_SAT_MODE	SimpleParameter	2025-03-17T02:01:51.213	2025-03-17T02:01:51.213			HKTMR	ACKNOWLEDGED	DANGER	DANGER

Figure 7: Ground Monitoring view on VIMA with several alarms

Several ground monitoring enabled us to detect mild signs of anomalies before they become more important. Typical examples are listed below:

- About the RW, some monitoring watched over the current consumption of the equipment and triggered when the wheels started to face friction. Thus the teams could follow the evolution of the anomaly and anticipate the failures.
- A monitoring watched over the precision status of the GNSS’s data. When the precision is not sufficient, the satellite central software stops retrieving the time from the GNSS and uses its own clock. But that induces a time drift of 300 milliseconds per day that could in the end impact the operations. Sometimes, the precision status froze at a wrong value, maybe due to SEU, and this monitoring warned the operational teams to take action and to reboot the GNSS.
- Some monitoring watched over the temperature of the payload which have to stay under some high and low operational limits. At the beginning of the SmallSat life in orbit, the monitoring triggered and the experts realised that the calibration of the payload heaters had to be completed. So we have executed exceptional operations to modify the target temperatures of the heaters.

4.2 Automated routine operations

To continue to simplify the routine, several periodic operations have been automated through the SOO on ground. The SOO makes it possible to schedule operations depending on the month, day, hour, pass order within a day or depending on the selected configuration, with a satellite in nominal mode or in survival mode for example.

4.2.1 Monthly checks

Thanks to this possibility, the Operators or the Ground Control Team, scheduled on every first Tuesday of the month, on the first pass during working hours and if the satellite is in nominal mode, a health check of the solar sensors. When this is the right moment, the SOO autonomously executes the right FCP to switch on the sensors, to activate the related housekeeping packets and to switch off the sensors with time-tagged TC after a delay (the sun sensors are necessary in satellite survival mode only). So the Flight Control Team does not have to worry about the scheduling of this recurrent and safe operation.

In the same way, we scheduled a dump of all the memory images of the central software every first Saturday of the month. It is visible in Figure 8 below with the boxes labelled ‘check checksums…’. It enables us to check if there is any corruption of the software memory content.

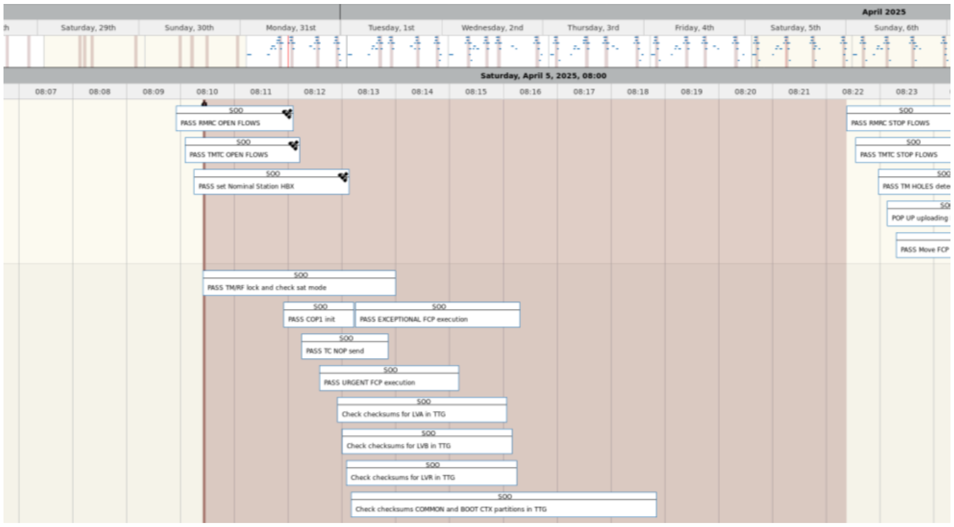


Figure 8: April first Saturday scheduled activities in the SOO

And to handle the long-term monitoring of the SmallSat and its equipment, we used the DAISY tool of the CCC to generate a monthly report with graphs displaying critical TM parameters. Thus, we can easily track parameters from launch to several years later and detect slow tendencies that can only be seen with enough step back.

4.2.2 Weekly checks

We also used the SOO to schedule a global platform check of all the main PUS services and subservices of the SmallSat every Sunday. It asks for TM reports of the PMON and event action statuses, packet store configuration or ON/OFF status of the equipment and compares the results with the expected values in nominal or in survival mode. If the result is different from the expected one, then the activity box inside the SOO turns yellow and the operators tell the Flight Control Team to have a look at the results. This procedure allowed us several times to realise that the on-board configuration was not the expected one, particularly after exceptional or contingency operations which had modified it. So it was very useful.

On Figure 9 below, is presented a typical view of the SOO showing Sunday's first pass activities in working hours. The platform check activity, with the label 'Check the PF configuration', finished here with a warning status identifiable with its yellow color.

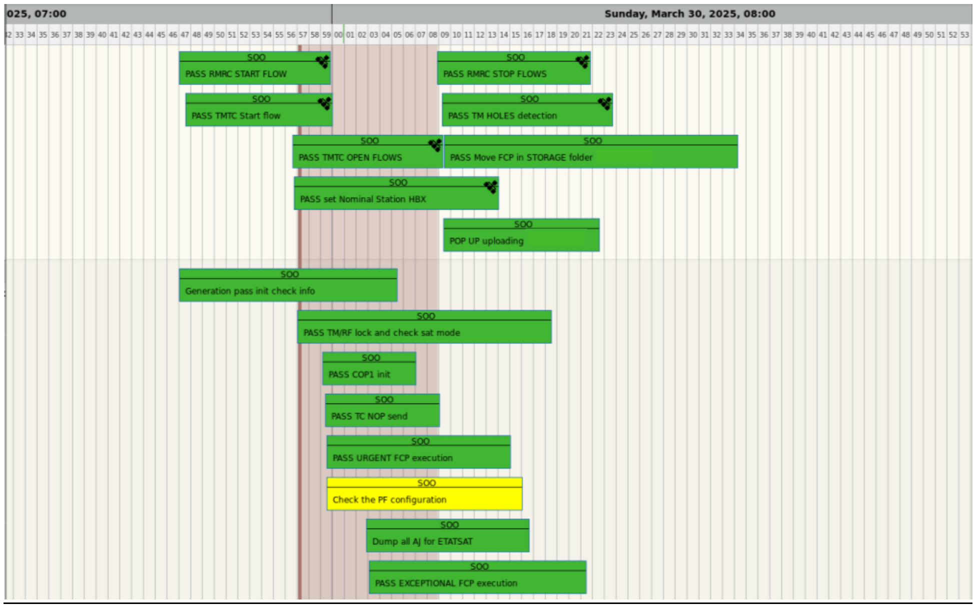


Figure 9: Sunday scheduled activities in the SOO, with a warning status

4.3 Validation and upload of a new central software

For the needs of the second RW workaround (subsection 3.3.3), a new version of the central software and its related ground data base were delivered by the manufacturer to the CCC. The delivery respected the ISIS format expected in this case so that it could be handled by the tools of the ISIS CCC.

The members of the Flight Control Team were responsible for the integration of the new software, regarding the existing FCP, ground data base and operations. With the help of the other operational teams, they followed a number of activities to prepare and execute the upload and to ensure that the update would go well:

1) Application of some overload patches and addition to the delivered data base, to include the ground monitoring and ground parameters for example;
2) Generation and deployment of the final data base on a test line of the CCC;
3) Generation of the FCP to upload the new software;
4) If needed, modification of existing FCP impacted by the update or creation of new FCP;
5) Tests of the upload on a simulator and non-regression tests;
6) Tests of the new features brought by the new software;
7) Final "go/no-go" review with the project, the operational teams and the manufacturer;
8) Upload operations from the nominal line with the final data base.

These activities are documented and have to be done by every mission using an ISIS CCC in case of a software update. The generation tools to create the FCP for the upload have been developed by previous missions like SWOT and now, smaller missions can benefit from it.

And we may have the opportunity to upload a new software again! Indeed, our CNES' GNC expert thought about an innovative solution to overcome the failures of the RW 3 and 4 that stopped us from doing the mission (described at the end of subsection 3.3.3). It may be possible to modify the GNC software to enable the SmallSat nominal mode to work with only one RW. The selected RW would be enough to continue the mission at the cost of slower pointing transitions. This would come through a new software that will have to be validated and uploaded following the above steps too.

5. Conclusions

As illustrated in this paper, the operations of our SmallSat have not been a long quiet river. The numerous transitions to survival modes because of SEU or equipment failures have taken up many days of the operational teams. Hopefully, most of the anomalies have been well overcome with ingenious ground and board workarounds for the GNSS and the first RW anomalies. In addition, there were much more unexpected problems than on other bigger satellites operated at CNES, but the teams successfully used the best of the ISIS CCC features and its implementation of the PUS to automate the routine activities and to supervise the SmallSat health regularly with limited effort. We have also benefited from the previous developments to manage critical operations like the upload of a new on-board software. At the end, the deterioration of the RW became the most serious threat of a mission interruption. But as said at the end of the last subsection we are thinking of a new on-board workaround that could extend the mission by several months or more. If it works, we will certainly have new anomalies to deal with and surprises as time goes by. All of this could be the opportunity to write a second paper about new thrilling SmallSat operations maybe!

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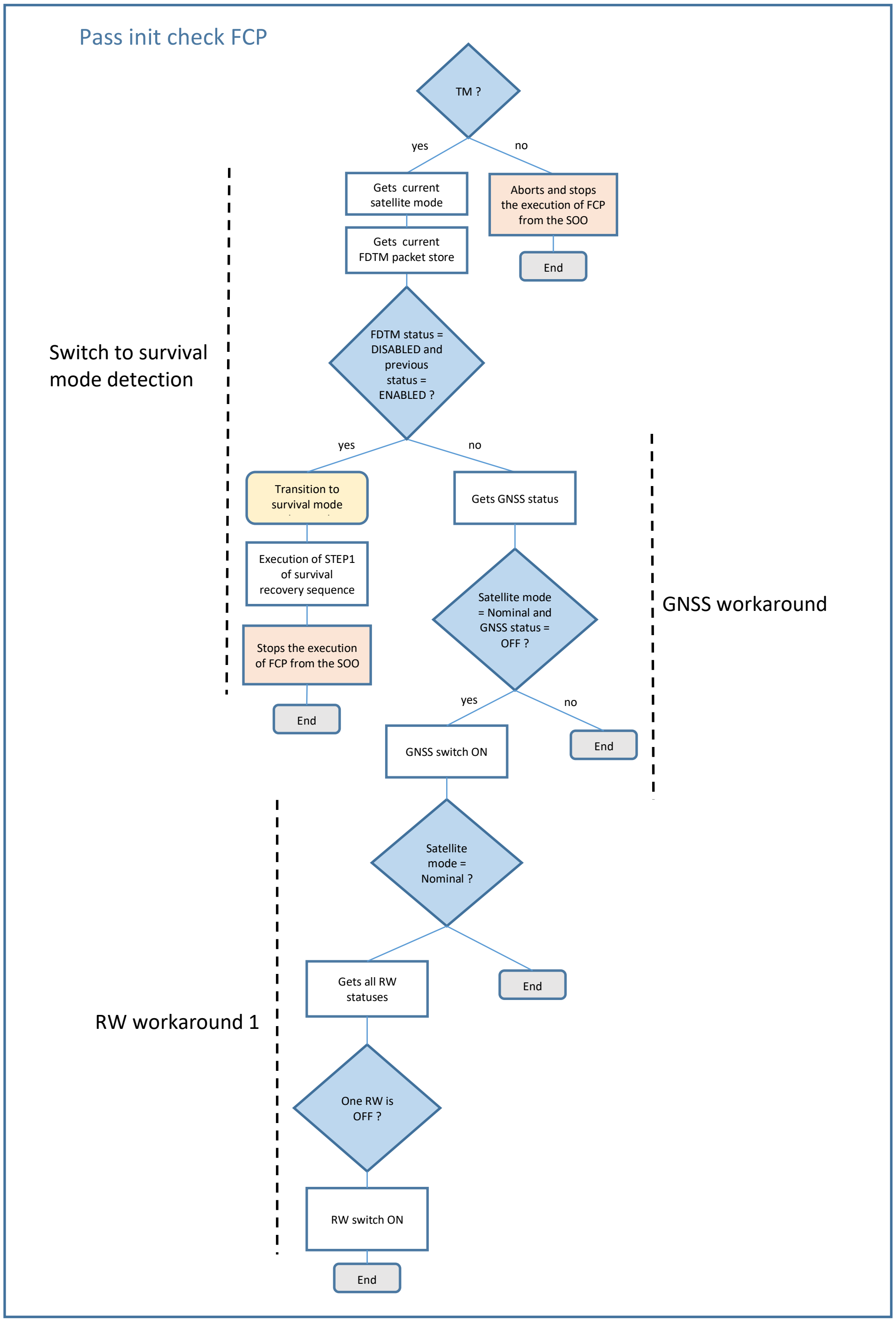
- All the other people involved in the operations of the SmallSat described in this paper

Appendix A (Logical sequence of the PASS_INIT_CHECKS FCP with all the workarounds)



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