CHALLENGES AND CREATIVITY IN THE OPERATIONS OF THE THREE SENIOR ESA PROBA SATELLITES

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Abstract

In the total of 45 years of combined operations, the three ESA PROBA micro-satellites (100 to 150 kg) have redefined what can be done with a micro-satellite. By applying simple and powerful design solutions and autonomy concepts, they proved that micro-satellites provide 'big-mission' return and reliability in a small package and a low-cost context. The three PROBA satellites are however becoming seriously 'senior', with the oldest, PROBA-1, in orbit since 2001, thereby being the longest operations ESA Earth observation mission. With age comes wisdom, but also a variety of different challenges to keep the satellites operating nominally, fulfilling their scientific tasks within strict requirements. This paper provides an anthology of different challenges which were faced, how they were resolved, with the focus on a PROBA-V issue, and how this led to the development of the 'P200' satellite platform.

Keywords: PROBA, SmallSat, EarthObservation, SolarWeather, Satellite, P200

1. Introduction

In October 2001, PROBA-1 was launched as the first member of the PROBA family, followed by PROBA2 in November 2009 and PROBA-V in May 2013. Although built to work for a couple of years, all 3 are still fully functional and providing payload data to users on Earth. But aging satellites, provide a number of challenges to keep them operating nominally. Solutions typically require ingenuity and creativity of the satellite designers and operators, whether they are solving a small glitch or a major problem. Implementing these solutions and seeing the effects on stability and availability or the overall performance of the satellite is a strong motivation to keep finding them, lengthening the life of the satellites and keep providing valuable payload data to the users.

In this paper, the 3 PROBA satellites are shortly introduced and some specific issues and solutions are highlighted and explained. All the lessons learned are injected into a new standard P200 satellite platform, built by Redwire Space (formally known as Verhaert and QinetiQ Space). This satellite platforms offers a low-cost, highly reliable platform, built according to ESA quality standards, and able to accommodate a variety of payloads. Three P200 missions are currently in the implementation phase.

PROBA stands for PRoject for OnBoard Autonomy. From the very first design phases, up to the in-orbit operations, everything is oriented to achieve smart operations. This means a maximum autonomy and automation, both onboard and onground, but keeping everything simple and pragmatic. The satellites fall in the micro-satellite category, weighing between 94 and 136 kg. The PROBA satellites are part of ESA's In-orbit Technology Demonstration Programme, missions dedicated to the demonstration of innovative technologies.

2. PROBA-1

2.1 Mission

PROBA-1 is the first ESA micro-satellite, aiming at flight-testing new space technologies. Major innovations were the then novel gallium-arsenide solar cells, the use of star trackers for gyro-less attitude control and one of the first lithium-ion batteries – now the longest such item operating in orbit – and one of ESA's first ERC32 microprocessors. The platform and the payloads (mainly Earth observation) has a total mass of 94 kg. The satellite was designed for 2 years, but is still functioning nominally. It was launched in 2001 from India on a PSLV rocket. It's overall objectives were:

- in-orbit demonstration and evaluation of new hardware and software spacecraft technologies
- in-orbit demonstration and evaluation of onboard operational autonomy
- in-orbit trial and demonstration of Earth observation and space environment instruments

PROBA-1 has 2 primary payloads. The Compact High Resolution Imaging Spectrometer (CHRIS), used to explore the capabilities of imaging spectrometers on agile small satellite platforms. The High Resolution Camera (HRC) is a black and white camera with a miniaturised telescope.

Fig. 1. PROBA-1 image of Egypt's Giza Pyramid Complex was acquired on 6 January 2018 (image credit: ESA)

PROBA-1 rolls in its orbit to take images: the satellite's platform and payload work as one. Like a photographer panning to snap a moving target, it follows the target and takes images from up to five different angles (-55º, -36º, nadir view, +36º and +55º).

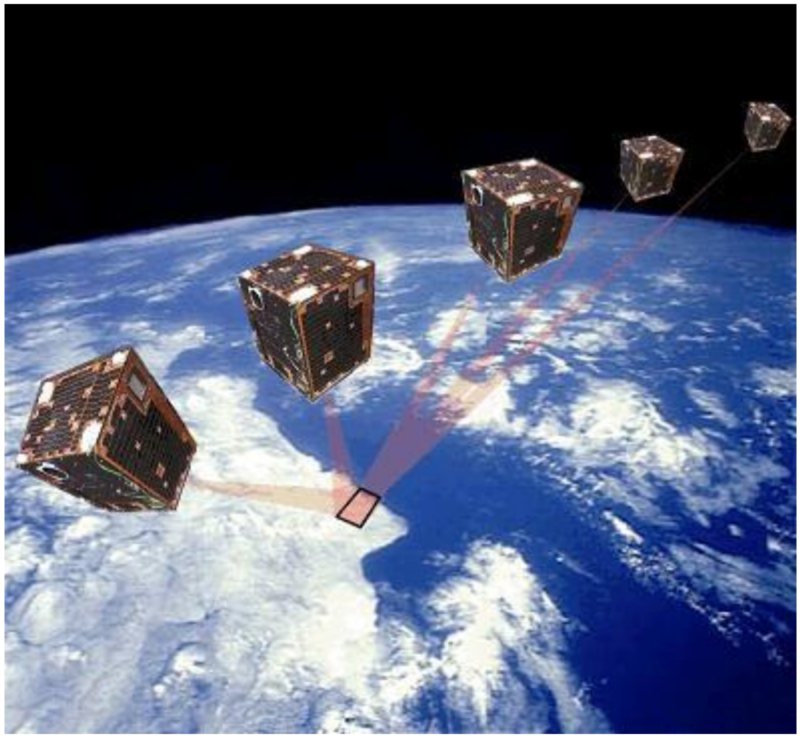

Fig. 2. PROBA-1 agile imaging

Launched in 2001, the satellite is now 22 years in-orbit, functioning normally [5] [6] [7] [8] [9]. But it needs to adapt continuously to a new environment, for which it was not designed.

2.2 Orbital drift and thermal impact

PROBA-1 was launched by PSLV into an sun-synchronous orbit with a local time of descending node at10:30am. As PROBA-1 has no propulsion, the orbit injection was crucial. The orbit was chosen so it would advance up to 10:46 within the first three years and then gradually drift backwards. This strategy worked as expected and provided very good local times for about eight years. The drift however continued to the extent that PROBA-1 entered a dusk-dawn orbit. This orbit with no or very little eclipse, provided a completely different thermal environment for the platform and payloads. A true challenge when the satellite has a passive thermal control system. It lead to a long period in safe mode during the winter months of 2011-2012. In safe mode attitude, the star tracker detectors get too warm, making it not possible to return to a 3-axis stabilised geodetic-pointing mode. Lessons were learned however and clever analysis allowed to continue nominal operations with smart changes in attitude, leading to cooler star trackers. The solution consisted in reducing the sun exposure of thermally sensitive surfaces by providing a pointing offset to the satellite. This pointing offset needed to be updated every few days to follow the orbital drift. Luckily, an already existing guidance mode could be used for that purpose: the 'high power' mode initially designed to maximize the incoming power on the solar panels has been exploited to minimize sun illumination on other panels.

Currently PROBA-1 has drifted even further, with currently a local time of descending node at 3am. In the first part of his life, PROBA-1 imaged earth targets in the downward arc of the orbit, as that was the arc in daylight. In the second part, PROBA-1 is now imaging on the upwards arc. PROBA-1 is highly autonomous. PROBA stands for Project for OnBoard Autonomy. To change the autonomy with respect to imaging on the upwards arc, a software patch was prepared on ground and uploaded to the satellite. Not straightforward with a +15 years old software development environment, but it proved to be successful, allowing to continue the Earth observations with PROBA-1.

2.3 Eye surgery for the star trackers

After more than a decade in-orbit, the increased temperature and the continuous bombardment by charged particles built up bright points on the star tracker CCD. This phenomenon began to camouflage actual stars. DTU, manufacturer of the star tracker resolved this issue by implementing a software patch, in order to better distinguish bright points from actual stars [1]. Such hotspots correspond to single pixels, while stars extend beyond single pixels exhibiting lens effects. The challenge comes as radiation hits accumulate, having two, three or more adjacent pixels impaired. Proba-1 ended up perceiving three to four times more hotspots clusters than stars.

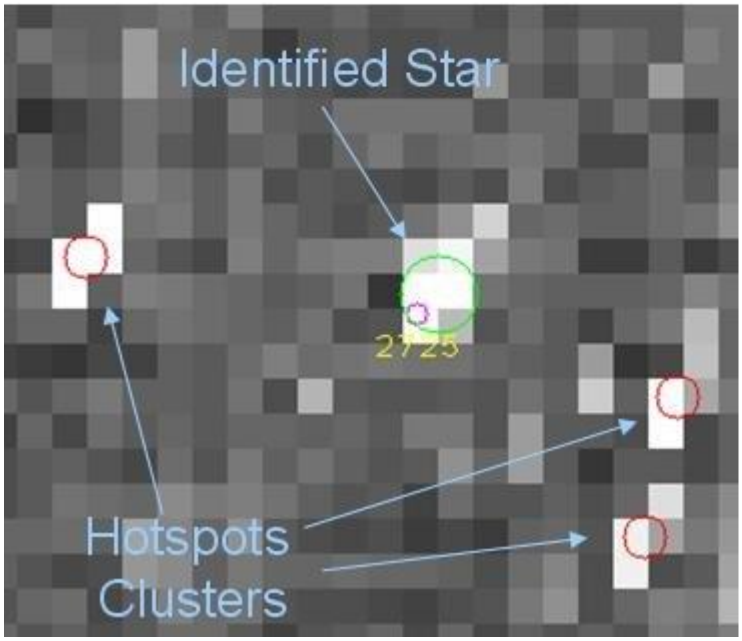

Fig. 3. PROBA-1 star tracker CCD hotspot clusters hide stars [1]

The improved algorithm, which extended PROBA-1 lifetime, was also included in subsequent missions, like ESA's Smart-1 Moon mission, the Sun-monitoring Proba-2, gravity-mapping GOCE and the Swarm satellite constellation. It is now part of the standard functionalities of the star tracker.

3. PROBA-2

3.1 Mission

The PROBA-2 satellite embarks 17 new technological developments and four scientific experiments. It was launched in a very stable dusk-dawn orbit in 2009. With so many new technologies, the mission, among the smallest ever flown by ESA at that time, has made a big impact in space technology. It provided flight-testing opportunities for a variety of different technology experiments. Amongst many others, it flight-tested a new type of lithium-ion battery (SAFT), an advanced data and power management system (Verheart, now called Redwire Space), combined carbon-fibre and aluminium structural panels (APCO) and new models for reaction wheels, star trackers and GPS receivers.

The mission has 2 primary payloads, both solar observation experiments:

- a Large Yield Radiometer (LYRA) that monitors four bands in a very wide ultraviolet spectrum, with Centre Spatial de Liège as lead institute supported by the Royal Observatory of Belgium as scientific leader and with an international team comprising PMOD (CH), IMOMEC (BE) and BISA (BE)
- an extreme-ultraviolet telescope (SWAP) using new pixel sensor technology (APS), that makes measurements of the solar corona in a very narrow band, with Centre Spatial de Liège as lead institute supported by the Royal Observatory of Belgium and with an industrial team comprising Alcatel-Lucent (BE), AMOS SA (BE), DELTATEC (BE), Fill Factory NV (BE) and OIP NV (BE)

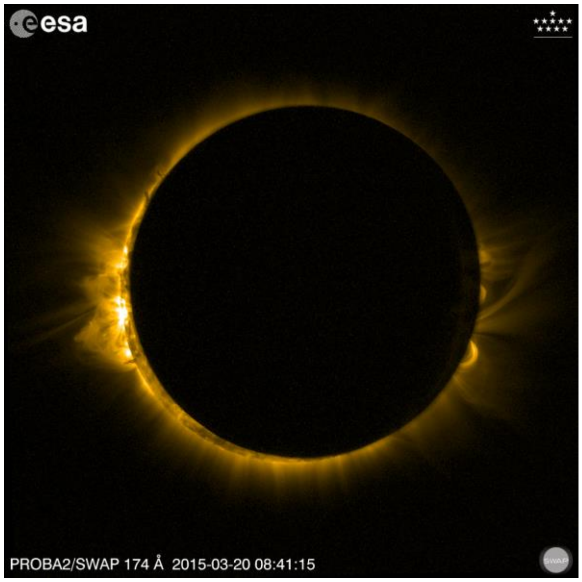

Fig. 4. PROBA-2 SWAP image showing a solar eclipse. (image credit: ESA & Royal Observatory of Belgium)

Although designed for 2 years, PROBA-2 has now exceeded 13 years of operations. It has far exceeded the expected return and still continues to image the sun, sending a massive amount of images to ground [11] [12].

3.2 On-board time wrap-around

The on-board computer of PROBA-2 provides a timer capable of counting up to 8.5 years. For a mission with a planned duration of 2 years, this is the least of the worries of the operators. But on May 6th, at 03:04:48 UTC, PROBA-2 was 8.5 years in orbit and the on-board time reached its maximum value and restarted from 0. The satellite was commanded to safe mode prior to the event to ensure a stable configuration during the never-tested event. Apart from resetting the on-board time filter and modifications on the ground side related to time-tagged telecommand and time correlation of satellite telemetry, no major issues were experienced. Similar wrap-around on PROBA-1, ensured the operations team was well prepared. On-board GPS receivers typically have a similar issue with the GPS week number (called a rollover). Also this was handled without major disturbances for the mission.

3.3 Additional technology demonstrator after 8 years in-orbit

At the end of 2018, a new on-board software was uploaded to PROBA-2. This software included an additional (software) technology demonstration to compress housekeeping packets based on the ESA POCKET technology. The in-orbit demonstration showed amazing results with compression factors of 3 to 5, with very minimal impact on the CPU [2]. This allows to reduce the bandwidth needs for housekeeping or allows the increase of the housekeeping rate without impact on the bandwidth. This could be extremely valuable for deep-space missions, where bandwidth is typically minimal and shared between platform and payload. All the future PROBA missions have this technology on-board.

Adding a housekeeping compression algorithm to the PROBA-2 on-board software, eight year after launch, was achieved in close co-operations with Spacebel, who developed the original PROBA-2 software and also had an implementation of POCKET from other projects. Testing was first performed on ground, on an engineering model of the platform on-board computer. The software update was combined with a series of other minor fixes and patches accumulated over the course of the mission. This update also allowed to retrofit updated software functionality from PROBA-1 and PROBA-V into the PROBA-2 software. The upload was completed in a single day, causing very little interruptions of the routine operations.

3.4 Fixing the redundant star tracker

In 2015, the redundant star tracker electronics showed an issue, where it continuously and autonomously rebooted after activation. The mission continued nominally on the primary star tracker, while investigation together with DTU were performed to find the root cause. The problem was pinpointed to the transfer of star tracker image data to RAM. DTU, supplier of the star tracker managed to pin-point the issue after an elaborate investigation. The platform allowed to perform investigations on the faulty redundant star tracker electronics in parallel to the nominally functioning primary star tracker. DTU provided a fix for this in the form of an FGPA update, which successfully resolved the issue and fully recovered the redundant star tracker processing unit.

4. PROBA-V

4.1 Mission

PROBA-V is the third satellite from the PROBA family and the first to be designed and operated as an operational mission (as opposed to technology demonstrator mission). It is based on a small, high performance satellite platform and a compact payload. Launched in 2013, the main objective of PROBA-V as an operational mission is to continue the data acquisition of the Vegetation Instruments on-board the CNES SPOT 4 and SPOT 5 satellites. The PROBA-V platform has inherited many technological choices of its PROBA-1 and PROBA-2 predecessors, improving a number of elements to cope with the demanding mission-specific requirements. PROBA-V, as the other two PROBA satellites, has no propulsion system on-board and can therefore only control its attitude, not the orbit. PROBA-2 has a propulsion technology demonstrator experiment on-board, but this is not suitable for orbit maintenance.

The main instrument onboard PROBA-V, designed, assembled and verified by OIP (Belgium), is the Vegetation Instrument. It is a high spatial resolution push broom 4-spectral bands imager with a Field of View (FOV) of 102º. This is realized by coupling of three identical Spectral Imagers (SI’s) and allowing the 2-daily imaging of the entire Earth land coverage. At the satellite’s 820 km altitude, the field of view allows a swath of 2282 km, with a Ground Sampling Distance (GSD) of 96m at NADIR. This compared to that of the SPOT Vegetation Instrument that provided a 1km GSD at NADIR.

The PROBA-V satellite is highly autonomous, requiring no ground commanding to image all land areas of the world, de-activating the imaging of sea-only scenes. The satellite switches the 3 camera’s based on the inputs of GPS, star tracker and an on-board land-sea mask [3]. Next to the vegetation instrument as primary payload, in good PROBA tradition, the satellite also embarks 5 technology demonstration payloads.

- An X-Band transmitter based on the new GaN RF amplifier
- An Energetic Particle Telescope (EPT), demonstrating a new type of radiation monitoring sensors and acquisition system
- An Automatic Dependent Surveillance Broadcast (ADS-B) receiver, demonstrating potential air traffic surveillance from LEO satellites
- A SATRAM radiation monitoring system, complementing EPT
- HERMOD (fibre optic connectivity in-situ testing)

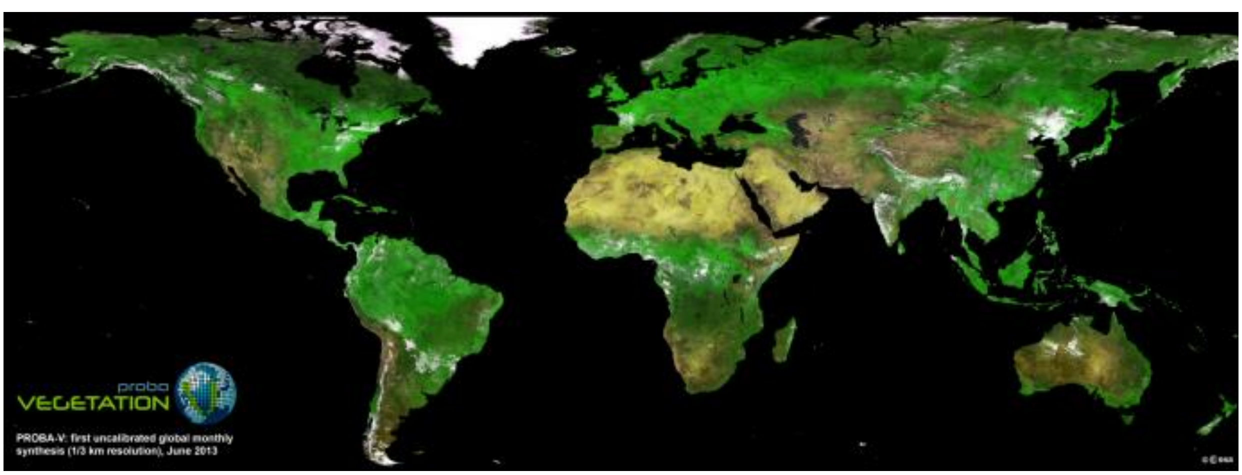

Fig. 5. PROBA-V first 30 days synthesis. (image credit: ESA & VITO)

PROBA-V was designed for a 2.5 years lifetime, but continues to function nominally. As PROBA-V has no control over its orbit, similar to PROBA-1, the local time drifted considerably after 7 years in-orbit. This degrades the light conditions for the payload to the extent that continuous scientific operations were suspended on 31 October 2021. Technology experiment operations however continue [13] [14] [15] [16] [17].

4.2 Technology demonstrator disturbing GNSS Receiver

During the commissioning phase, it was found that the GNSS receiver lost lock occasionally for unknown reasons. More investigation concluded that when the ADS-B receiver was activated, it disturbed the GNSS receivers ability to get a lock on the GPS signals. All PROBA satellites implement the standardised ESA PUS (Packet Utilization Standard) services, including monitoring, event and event-action services for FDIR. Ground has full control to add/remove/update these monitors, associated events and event-actions. A new monitor was added to detect a GPS loss of lock when the ADS-B receiver was active. The event would then trigger 2 actions, the first one being to power OFF the ADS-B. As the GPS lock is vital to meet the geo-location performance of the primary payload, it has a higher priority than the technology demonstrator. A second action releases a relative time-tagged TC to re-activate the ADS-B after 10 minutes, allowing the GPS to regain lock in the meanwhile.

The above is an example of continuous tuning of FDIR to cope with unexpected behaviour and a changing environment when the satellite becomes older and the orbit changes.

The problem was however fixed more permanently by an FPGA update of the ADS-B receiver, reducing the amount of occurrences dramatically.

4.4 Achieve 99.6% availability with a power-cycle every 55 hours

PROBA-V is in general fully redundant, having a redundant unit for each function. This is also the case for the on-board computer (OBC). This OBC has 2 lanes (primary and redundant) and a Reconfiguration and Emergency Module (REM) in-between. The OBC operates in cold redundancy, so only one lane is active at the time. The REM is continuously active and contains a small safeguard memory (SGM) accessible by both OBC lanes. The REM also ensures that the OBC time is maintained, even after a switch-over and power cycle.

A few days after launch, a latch-up was detected in a SRAM memory component within the on-board computer. This was detected by an increased current consumption of the primary on-board computer and the reporting of un-correctable bit errors in the SRAM by the memory scrubber. No autonomous FDIR was implemented for this specific failure case prior to launch. The same SRAM chip had been flown on other PROBA missions and ground testing confirmed that the SRAM module was very resistant to radiation-induced latch-ups. Further assessment on ground showed that although the SRAM component had the same lot and date-code as other SRAM modules used, the die used inside of the component was different and more prone to radiation induced latch-up. The latch-up was non-destructive, but could only be removed by power-cycling the on-board computer.

This power-cycle can be performed by commanding a switch-over to the redundant lane of the OBC and then a switch-back to the primary computer by command from ground. This was performed in the early commissioning phase, impacting the commissioning activities significantly due to the reboot-related operations. Operators do not believe in coincidence and what was feared became true: the component latched again within a few days. From ground, the operator power-cycled the computer each time at the first satellite contact after the latch-up occurred. As PROBA satellites are highly autonomous, an operator is only present during work-days and working hours. This causes issues if a latch-up would happen during a weekend. After several manual power-cycles commanded by an operator, an automated flight operations procedure (FOP) was built to automatically power-cycle the computer in case of the issue. This provided unattended recovery during the night or weekend. The FOP ensured that all nominal operations automatically continued, including restart of the payload acquisitions. Thanks to the extensive experience gained on PROBA-1 and PROBA-2 related to operations automation, making this FOP was done in a couple of hours.

Although this was an improvement, it still meant loss of availability as a recovery was only possible at the next ground contact (about 3 per day). The time in-between the latch-up and the ground recovery was lost for payload acquisitions as the payload images was not stored in case of the SRAM latch-up.

A permanent solution was found in a smart software update which would perform a full power-cycle autonomously on-board and restart all the activities to resume payload acquisitions. Using this solution, the issue is removed and fully recovered in less than 3 minutes.

The solution works as follows:

- A very small part (0.5%) of the mass memory (flash) of the OBC lane was reserved for 2 types of data:
    - A backup of the platform stores, where platform TM is stored in-between passes. Nominal platform stores are located in the SDRAM of the OBC, which is cleared after a power-cycle. This allows to dump the platform housekeeping after a power cycle to ground to avoid having big gaps in satellite platform data.
    - An area where contextual data is stored in order to resume nominal operations immediately after the power-cycle. This contextual data contains the full on-board schedule, GPS information to allow a warm-start of the GNSSR, configurations of the payload, etc. This area is written on request by a ground command after each S-band contact, as only during the S-band contact this context information is updated.
- A monitor is added to detect the SRAM latch-up based on the amount of un-correctable bit errors found in the specific memory. The scrubber is also increased to the maximum rate to ensure detection asap after a latch-up event.
- If an SRAM latch-up is detected, the active OBC writes a short message in the REM SGM, before it commands a switch-over to the redundant lane. This message contains a number of parameters to ensure the redundant OBC can know that it should immediately command a switch-back to the primary lane. The parameters include the lane commanding the recovery, the satellite time of the switch-over, the switch-over reason, the active system mode and some other low-level data.
- After the primary OBC commanded the switch-over, the redundant OBC would power up. After boot, the software would immediately read the latest REM message. If the message was very recent and the reason was an SRAM latch-up, the redundant OBC would command again a switch-over, resulting to a switch-back to the primary lane. This basically then results in an autonomous power cycle on-board for a system not designed to be able to perform a power cycle.
- When the primary OBC then boots again, it also reads the latest REM message. Based on the parameters, it will define the action to do. If the message is recent, it would command the system mode from before the latch-up and recover the contextual information from the mass memory (flash). This would return the satellite in the exact configuration as before the latch-up, allowing to continue payload acquisitions within minutes.

The above mechanism works for a latch-up detected on both primary or redundant OBC lanes. The REM message contains a parameter on which lane wrote the message, allowing to use the exact same algorithm on both OBC lanes. This meant that both OBC lanes still fly the exact same software, after the update. The mechanism also ensures that no continuous ping-pong can occur and that a switch-over for any other reason does not result in a switch-back.

The implemented autonomy in the payload operations proved to be extremely valuable and an enabler for the above functionality, as with a single command, the payload restarts imaging according to the land-sea mask, not requiring extensive uploads of detailed command schedules.

PROBA satellites have an additional functionality which proved extremely valuable for this behaviour. There is a list of start-up telecommands in the flash of the OBC. This is persistent memory, so is available after initial boot, reboot or a power cycle. The start-up telecommand list can include 450 telecommands, which are executed immediately after the boot of the platform software. Ground can populate this list as needed. The list can contain any type of commands, making it extremely flexible. Examples are:

- the definition of housekeeping packets, such that after each boot, the platform software has a set of predefined housekeeping packets defined and active. This removes the need to include these definitions in the software compilation process itself. If a housekeeping packet is changed during a mission, the start-up telecommand is updated, but no platform software patch is required, while after boot the new definition is used.

- update of FDIR during commissioning. Typically during commissioning some FDIR settings are tuned. These can be done on the running software, but in case of a reboot, the software will return to the launch default. To avoid a patch of the software for this, the FDIR is updated using a start-up TC list.
- loading of OBCPs, patching of configurable parameters, activation specific units after boot, changing preferred units, update AOCS parameters, etc. All minor activities where the power up default of the software needs to be changed. For each of these changes, a start-up telecommand is added, avoiding an expensive, inflexible and long process to update the flight software image in the flash.

With the update, the latch-up detection, the full switch-over and switch back is performed autonomously on-board. This provides a full recovery of the issue, within 3 minutes and smooth continuation of all the mission and payload imaging activities. All without the need for neither ground contact nor an operator. More than 8 years later, this automatic recovery happened more than 1000 times! The impact on the mission is neglectable, with an overall availability of the satellite of 99.6%.

5. The next generation – the P200 small satellite platform

The experience of 45 years of combined operations of the three ESA PROBA satellites is priceless; Redwire space is therefore privileged to include this heritage in the development of the next evolution of the PROBA platform, the 'P200'. The P200 is capable of supporting payloads up to 100 kg and targets 200-300kg class missions, compatible with typical shared launch opportunities and small satellites launchers. The P200 preserves the fully redundant design, market-leading pointing performance and the PROBA high level of autonomy, opening the door to low operating cost and very high system availability.

Meanwhile, the P200 platform is currently in production for 3 missions, the ALTIUS mission [22], the IOD/IOV Element 1 (with D/TEC) and 1 for a commercial customer, demonstrating the flexibility of the P200 to accommodate a multitude of different payloads and serve wide range of mission. In times of rapid development of new satellite platforms, the P200 platform is an cost-effective assurance for reliability and performance [4].

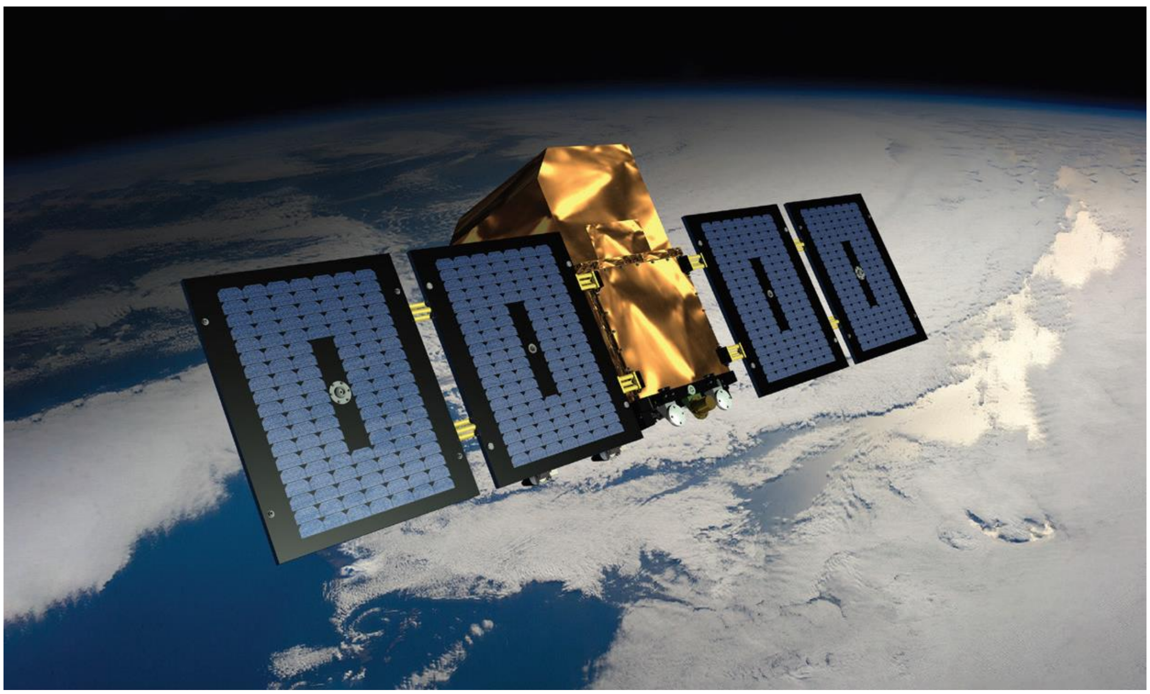

Fig. 7. P200 platform rendering

Fig. 8. P200 platform STM model

6. Conclusions

When satellites get older, the environment changes, components show degradation, issues occur. With ingenuity and creativity of the satellite designers and operators however, solution can be found in most situations. These solutions extend the mission lifetime of the satellite and increase the return for the users. The PROBA satellite series is a perfect example of this. Redwire Space, formerly known as QinetiQ Space, as prime, with invaluable support of ESA (ESTEC and ESEC), Spacebel (software subcontractor), DTU (star tracker subcontractor), and many other subcontractors have demonstrated this, extending a combined design lifetime of 4,5 years (3 PROBA's) to more than 44 years (01/2023), with all 3 satellites still healthy and operational. With the new P200 satellite platform, built on this huge heritage, the tradition of high-performance, extremely reliable, while remaining cost-efficient satellite platforms continues.

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