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OPS-SAT LEOP and Commissioning: Running a Nanosatellite Project in a Space Agency Context

David Evans, Georges Labrèche, Tom Mladenov, Dominik Marszk
European Space Operations Center (ESOC), European Space Agency (ESA)
Darmstadt, Germany; +49 6151 902720
david.evans@esa.int

Vladimir Zelenevskiy
Telespazio Germany GmbH
Darmstadt, Germany; +49 615 182 570
vladimir.zelenevskiy@telespazio.de

Vasundhara Shiradhonkar
Terma GmbH
Darmstadt, Germany; +49 6151 860050
vash@terma.com

ABSTRACT

OPS-SAT is a 3U CubeSat launched by the European Space Agency (ESA) on December 18, 2019. It is the first nanosatellite to be directly owned and operated by ESA. The spacecraft is a flying platform that is easily accessible to European industry, institutions, and individuals, enabling rapid prototyping, testing, and validation of their software and firmware experiments in space at no cost and no bureaucracy. The spacecraft is equipped with a full set of sensors and actuators including a camera, GNSS, star tracker, reaction wheels, high speed X band and S band communication, laser receiver, software defined radio receiver, and a 800 MHz processor with a reconfigurable FPGA at its heart. Conceived to break the "has not flown, will not fly" cycle, OPS-SAT has spearheaded many firsts. One of the reasons for the success of CubeSats is that they have changed the rules on who can access space; opening a world that used to belong to a few governmental and commercial players to smaller and newer ones. This is also true within space agencies as well as outside them. It would have been unthinkable just a few years ago for an ESA center, whose prime job is to control ESA satellites, to specify, design and launch a mission with the sole aim of improving mission operations. However, it was never going to be easy. This paper describes the events of the OPS-SAT mission starting from a few weeks before launch, when some last-minute non-compliances almost stopped the mission, through the LEOP and to the end of commissioning. During the whole process many challenges had to be overcome and it took ten months to complete commissioning compared to the initially planned three months. Problems started in the first pass, no UHF packets were received from the spacecraft and bad communications plagued the mission for many months. However, during this time a great deal of progress had already been made thanks to the ingenuity of the Flight Control Team (FCT) and the supporting industry. Given the unpredictable and short uplink possibilities a framework evolved whereby commissioning of the payload was done using the experimenter infrastructure rather than the flight control infrastructure.

INTRODUCTION

OPS-SAT is an ESA nanosatellite mission designed exclusively to demonstrate ground-breaking satellite and ground control software under real flight conditions. This makes it the first mission of its kind worldwide. The project is led by the European Space Operations Center (ESOC) in Germany underlining it as a mission designed by operators for operators. This paper describes the problems the mission faced starting from a few weeks before launch until the end of commissioning ten months later, and how these problems were overcome. To provide context, this paper first outlines the mission history, then it provides a summary of the space and ground segments, and finally states the overall mission objectives. Major problems are presented: starting from a few weeks before launch, until launch, in LEOP, and during commissioning. How these challenges were overcome to bring the mission into a productive state is then explained and a conclusion is given.

MISSION HISTORY

The OPS-SAT concept was proposed in 2011 and in January 2012 the ESA General Study Programme funded a feasibility study using the ESA Concurrent Design Facility in ESA/ESTEC. In March 2013, ESA released an open call for experiment ideas. Over one hundred experiments from 17 Member States were selected.

In 2015, the ESA General Support Technology Programme (GSTP) funded the space and launch elements of the mission with the following consortium: TU-Graz (technical prime), MAGNA STYER & UNITEL (Austria); GOMSpace (Denmark); MEW-Aerospace UG, Berlin Space Technologies (Germany) and finally SRC & GMV Innovating Solutions (Poland). The ground segment and operations elements were funded by ESA/ESOC.

The high-power demands of the spacecraft resulted in restrictive constraints on the allowed orbital elements. The most important was the requirement for a sun synchronous orbit with an LTAN between 6:00 AM and 9:30 AM. This excluded most launches and led to a long wait before a suitable rideshare opportunity became available. Tyvak International (Italy) were chosen as launch brokers and provided the deployer. The spacecraft was launched with Arianespace on a Soyuz from Kourou on December 18, 2019, following a one-day launch delay. Other small satellites on-board were ANGELS & EyeSAT from CNES and CHEOPS from ESA.

The mission had to deal with very bad communication problems in both UHF and S band due to a combination of onboard and ground station issues. These were not mitigated until 9 months after launch. Once communications became more stable the payload commissioning was completed within one month. The satellite experienced a major anomaly on January 1, 2021, when the main experimental processor failed to completely boot-up. After one month of investigation, it was decided to move to the back-up processor but in a completely different configuration for mitigation purposes. This was achieved in March 2021 and the mission has since resumed experiments.

SPACE SEGMENT

OPS-SAT can be viewed as two satellites in one. A CubeSat satellite along with an ESA satellite flying an advanced communications module and a very powerful on-board computer. There are various peripherals (camera, GPS, advanced ADCS subsystem) and two payloads of opportunity. The CubeSat bus consists of an on-board computer called the NanoMind, a power subsystem, a UHF communications subsystem and a basic ADCS subsystem. The mechanical architecture of the OPS-SAT is a 3U CubeSat structure with double folded deployable solar panels. It has a size of 10x10x30 cm (not including deployable) and a mass of approximately 4.8 kg. Two deployable solar array panels generate 30 W of electrical (peak) power. A system diagram is shown in Figure 5 of the Appendix.

The Satellite Experimental Processing Platform (SEPP) is the heart of the OPS-SAT. It is a powerful ALTERA Cyclone V system-on-chip (SoC) module with sufficient on-board memory to carry out advanced software and hardware experiments [1, 2, 3]. The device provides powerful processing capability with an 800MHz CPU clock and 1GB DDR3 RAM. It is the reconfigurable platform required on OPS-SAT on which all major experiments are processed. All Altera SoC SX devices consist of an internal Hard Processing System (HPS) and a Field Programmable Gate Array (FPGA) portion. The Altera Cyclone V SX SoC HPS is a fully functional computer and contains a dual core ARM CPU with several built-in hardware blocks and device interfaces. It has built-in error correction coding (ECC) features.

The system offers the possibility to use DDR2, LPDDR2 or DDR3 RAM. The ARM CPU is connected to many HPS hardware blocks. Bridges enable high speed data exchange between FPGA and HPS portions. The Linux *Ångström* distribution is used as the default operating system (OS) for the SoC. All HPS blocks can be accessed from the installed OS application software. The HPS portion must be configured at system start-up. The SoC configuration data is part of the SEPP software image stored in the external memory.

OPS-SAT contains two ADCS systems. One is provided as part of the bus and is referred to as the coarse ADCS. The control algorithms are implemented on the NanoMind On-Board Computer (OBC) and it relies on magnetorquers as actuators and sun sensors and magnetometers as sensors. The other is implemented as part of the payload and is referred to as the fine-pointing ADCS or iADCS. Experimenters can use this to carry out attitude control experiments and to provide higher pointing accuracy for camera and optical data transmission experiments. Control algorithms can be placed directly on the iADCS FPGA or on the SEPP. The iADCS-100 by Berlin Space Technologies (BST) has been chosen, allowing a pointing accuracy well below 1°. The iADCS provides a set of high-performance sensors and actuators such as the ST-200 star tracker and miniature reaction wheels. The iADCS-100 offers several autonomous modes, such as nadir pointing and target pointing. The optical camera used is the BST IMS-100, a space camera developed by BST based on the ST200 star tracker. It can provide still images as well as video, whereby image processing is performed on the processor core (SEPP).

Communication is provided in 3 bands, UHF, S and X. The on-board NanoCom unit provides a 9.6 kbps half duplex channel in UHF. The Syrlinks EWC27 EC31 transponder provides 256 kbps up and 1 Mbps down in S band and the Syrlinks EWC27 transmitter can transmit up to 50 Mbps in X band. Of note is the very high uplink rate which is needed to load the large software images to the spacecraft as part of the experiments. Both the S and X band channels can be routed through an FPGA loaded with the standard ESA IP core for TC decoders and TM encoders. This is referred to as the CCSDS engine. This ensures that OPS-SAT looks exactly like any other CCSDS compliant ESA spacecraft to the ground system as far as the framing layer is concerned. However, it is also possible to route the TM and TC signals directly from the receiver and transmitters to the SEPP FPGA thereby bypassing this IP core. This allows non-CCSDS protocols to be tested in flight.

One payload of opportunity is the optical communications experiment which provides a transmission rate of 2 Kbps using a small optical receiver which fits into OPS-SAT. A photon counting module with a built-in multi-pixel photon counter is the heart of this system. The optical receiver is connected to the SEPP so that uplink data can be received and processed by on-board experimental software.

The other payload of opportunity is the software defined radio (SDR). This is a very small radio front-end consisting of a tuner, down-converter and analogue to digital converter. Complex signal samples are delivered to the SEPP where signal processing (e.g., demodulation and decoding) is performed by on-board experimental software. This allows the monitoring and demodulation of radio signals for a wide frequency range. This includes the radio amateur UHF bands.

GROUND SEGMENT

The interactions between the ground and space systems are shown in Figure 1. The ground segment is centered around the European Mission Control Software, SCOS, which has been modified to handle the new application-level interface CCSDS MO Services [4, 5]. GMV Poland implemented the corresponding changes to the on-board software. The control is run from the ESA SMILE LAB in ESOC, which essentially consists of many, specific Virtual Machines (VMs) on the SMILE LAN which support the mission. These VMs include different instances of SCOS for testing and operations as well as for real-time command and control of the antennas, experimenter access and other data processing.

Three UHF ground stations are used; one at the Technical University of Graz, Austria, one at a facility in Cork, Ireland provided by LeafSpace and ESAs own UHF station at ESOC, Germany called ESOC-2, provided as part of the SMILE facilities. A single S/X band station is used at ESOC called ESOC-1. This is a 3.7 meter single parabolic reflector, which supports S band up and down links and X band down links, with an angular velocity of up to 10 degrees per second in a three-axis system.

The UHF baseband equipment is based on the GOMSpace provided units and/or software defined radio implementations. The underlying transport protocol is CSP packets on top of AX25 framing. The S band/X band baseband equipment is based around a CORTEX but again a software defined radio implementation is also available. The underlying transport protocol is MO packets on top of CCSDS framing. Extra protocols are available to command the SEPP over the S band link that include CFDP, TCP/IP and basic Linux shell access (called SpaceShell). File-based operations are used extensively when communicating with the SEPP – especially when loading experiments, software and firmware patches and downloading experiment artifacts. The mission uses CCSDS CFDP as the underlying protocol that will be used by the ESA EUCLID mission.

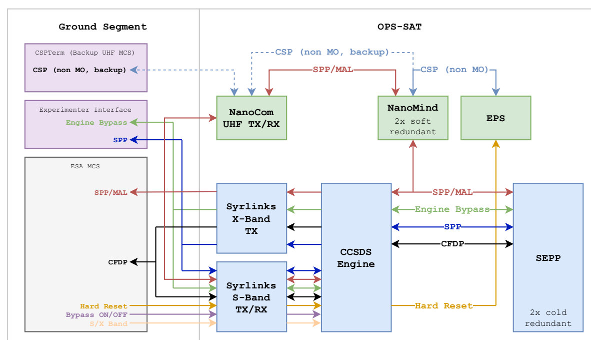

Figure 1: Interactions between ground and space systems.

MISSION OBJECTIVES

OPS-SAT looks like an advanced ESA spacecraft to the ground. The uplink rate is four times higher than any ESA spacecraft; it employs never flown before communication protocols and implements new ESA patents. By using many new technologies to control the mission every day ESA is preparing for the future.

At the center of OPS-SAT is a high-performance control processor. This allows "normal" software (Linux, Java, Python…) to control the entire satellite: rotate, take pictures, classify them, compress them, send them to the ground, etc. Together with the experimenters, the mission is exploring how all that processing power and open-source software can be exploited in space.

The processor integrates with a powerful FPGA that allows the FCT to reconfigure its firmware in space. Reconfigurable on-board software caused a revolution in space, and this will be just as significant. It is an incredibly powerful technology allowing many algorithms to run in parallel at nanosecond speeds. Together with experimenters the mission is learning how to master this powerful technology safely in flight.

European industry and institutions can use the platform to rapidly test their software and firmware experiments in space at no cost and no bureaucracy.

MAJOR CHALLENGES BEFORE LAUNCH

There were four major issues experienced in the few weeks before launch.

GPS failed the open field testing

Following satellite integration and environmental testing the spacecraft was taken outside of the clean room in a sealed box to perform a GPS field test. Unfortunately, the GPS unit only obtained a good position and velocity fix after many hours. An anomaly review board was convened, and many tests/configurations were conducted. Eventually it was concluded that the antenna was the source of the problem. The receiver unit itself had no problem obtaining a fix when connected to a cheap 10 Euro antenna. However, the implications of replacing the antenna at this stage in the project were highly disruptive and would have required a repeat of environmental testing. There was no longer the budget or time for this and so the decision to fly with the degraded antenna was made. It was hoped that the receiver would perform better in space as the signals do not have to traverse the atmosphere. Unfortunately, this was not the case. Although the GPS receiver has been able to get a position and velocity fix in flight it has not been very often. Investigations are still on-going to try and optimise the system to improve the situation.

Star tracker firmware needed updating

Shortly before spacecraft integration into the deployer and shipment, an urgent recommendation was given by BST to update the firmware of the iADCS star tracker. The latter is a separate optoelectronic module which interfaces through a UART connection to the iADCS. The software update was considered urgent as it vastly improved longevity of the image sensor in orbit. It was decided to proceed with the update as soon as possible. The star tracker is connected to the iADCS via a UART interface over which it is programmed. The method of flashing new software onto the star tracker consisted of first loading a "passthrough" bootloader onto the actual iADCS so that the star tracker could be programmed via the serial debug interface of the ADCS. The major challenge of the operation was updating the iADCS bootloader since the JTAG connector was inaccessible due to the already integrated satellite, therefore engineers of BST had developed a method to flash a new bootloader to the iADCS using the reset-line, which was the only pin of the iADCS that was accessible via the CubeSat PC104 stack connector (the JTAG connector was not connected to this stack). The programming via the reset-line only worked on a certain frequency and therefore a line accelerator was developed due to the higher capacitive load of this line in the integrated spacecraft. The passthrough bootloader was programmed, after which the star tracker was remotely updated through the serial interface. Finally, a newer version of the iADCS firmware was then also flashed which added the option of future software updates via the I2C interface in-orbit.

Non-compliance with respect to the deployer specifications

A few days before the satellite was to be delivered to the launch provider a series of satellite/deployer compatibility tests were carried out as part of this handover. It was found that the satellite was non-compliant in terms of volume. Analysis showed there was a slight bending of the double deployable solar arrays in the middle causing them to touch the deployer rails at the extremities, see Figure 2. A request for deviation was not granted by the launch broker and the only choice was to authorize TU Graz to dismantle the solar arrays and re-stow them in the hope that this would eliminate the non-compliance. This process was difficult as the solar array hinge screws had already been glued for flight and each had to be carefully removed first. Thanks to the assistance from the launch broker and some excellent emergency support from the solar array provider, the integration team at TU Graz managed to successfully perform these procedures eliminating the non-compliance. The satellite was accepted for delivery by the launch broker the next morning.

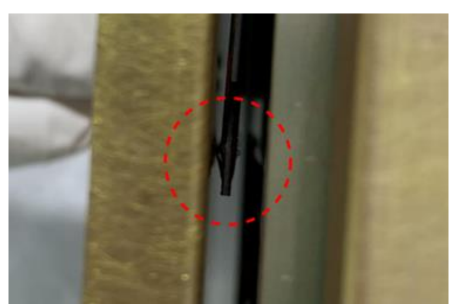

Figure 2: Non-compliance on volume causes the solar arrays to touch the deployer rails.

SEPP-1 failed to boot

Following environmental testing, it was seen that the SEPP1 unit sometimes failed to boot or sometimes hung during operations. Investigations revealed that the cause was that the communication with one of the three memory chips containing the DDR RAM on the HPS part of the SoC was failing. As the unit was not completely failed it was decided firstly to declare the SEPP2 unit as prime and secondly to create a plan to work around the problem should SEPP2 fail in orbit.

As a follow-on to this story, in January 2021 communications with the SEPP2 unit did in fact fail in orbit and the SEPP1 workaround plan had to be activated. Telemetry analysis of SEPP2 showed the currents from the power supply indicated it was not drawing enough power and it was therefore certain Linux was not booting. Due to the low currents, it was suspected the unit either failed to boot completely or was held in a reset state. Each SEPP unit has a reset line that has a pulldown resistor to keep it in reset by default (active low). The power unit that powers the SEPPs pulls this line high for the unit to boot. It was suspected that this reset line was unable to be pulled high by either a short to ground, or a problem in the Power Manager. The first action performed therefore was manually toggling the reset line via the Power IC bus expanders and reading out the physical state of the line to assess if there was a hardware failure. The latter confirmed the line was not shorted to ground. It was also confirmed via telemetry that it could be pulled both low and high. The latter operation did not influence the currents. Booting from redundant boot images stored in QSPI memory was also unsuccessful. Through analysis of the integration photos, it was found there was an excess of glue used to fix these chips to the board that may have reached the Ball Grid Array (BGA) connections. It is suspected that thermal cycling in eclipse may have caused the BGA connections to lift and induce this failure. The problem was occurring on a different chip than on SEPP1 but the failures could have a similar root cause.

In February 2021, TU Graz engineers implemented the workaround required to use SEPP1 while avoiding access to the HPS DDR RAM, effectively using the FPGA RAM instead. It is worth noting that the failure occurred in eclipse season and the operational concept involved powering on and off the SEPP 4–6 times per day. Hence, although operations have successfully resumed on the SEPP1 unit, it is only powered on and off when absolutely necessary to reduce thermal cycling as much as possible.

COMMUNICATION CHALLENGES IN LEOP

There were three major issues experienced during LEOP that negatively impacted spacecraft communications.

Very bad UHF communication link

The UHF connection was planned to be the prime communication channel for the LEOP. However, it turned out to be very unreliable, in fact no packets were received in the first pass. There were three main contributing factors to early UHF communication issues during LEOP:

1. Badly configured RX/TX switching timing on transceiver in space (solved by config change in space)
2. Worse than expected uplink link budget (solved by increasing uplink power at TUG ground station)
3. Usage of sub-optimal transmission mode (not solved as OPS-SAT needs to be compliant with amateur radio regulations)

During the first passes, communication attempts with OPS-SAT via the UHF ground station in Graz were unsuccessful. Early coordination with the radio amateur community allowed external signal reports to be sent to ESA in a predefined format. It was noticed that UHF telecommands were arriving and the spacecraft was replying with activity tracking messages, but the responses were only received by external ground stations and not by the mission's ground stations, hence TCs were flagged as unconfirmed in the mission control system. After the TX delay (wait time between reception of Telecommand and transmission of response) of the on-board transceiver was changed from 50ms to 200ms the UHF station at Graz was able to receive the responses and the first 2-way communications with OPS-SAT were carried out.

Early assessment of the uplink was done through monitoring the beacon telemetry from the on-board UHF transceiver which among other values indicate received packets, frequency error and uplink signal strength (RSSI) as well as background noise level. It was noticed that commanding via the TUG ground station had a poor TC success rate, while commanding via the LeafSpace ground station in Ireland (which had a lower uplink power) had better TC success rate with the satellite over the Atlantic. The background noise level measurements of the on-board transceiver indicated that it increased over Europe from -120dBm to -100dBm. When the satellite was in communications with the UHF station at Cork and over the Atlantic (where background levels were around -120dBm), communications were more reliable even with less uplink power. Figure 3 shows a plot of the background noise as measured by the transceiver in function of geographical location. Each sample represents the ground track position of the satellite at the time of beacon reception.

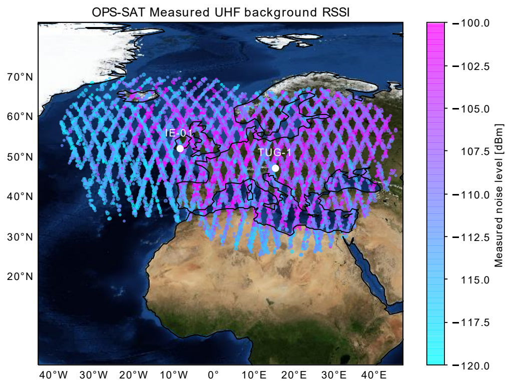

Figure 3: UHF background noise over Central Europe measured by OPS-SAT.

Station improvement and reconfiguration were performed at TUG. The uplink power was increased to combat the degraded uplink margin due to elevated noise levels received at the satellite transceiver. Communications improved although remain in the 50–70% TC success rate.

The UHF transceiver on the satellite was configured for mode 6. In this mode, an AX.25 modem protocol is used and frames are sent in a High-level Data Link Control (HDLC). This means that the individual frames are separated and synchronized using single "flag bytes." This is the only mode which is out-of-the box compliant with Amateur Radio spectrum as AX.25 is configured with callsigns. Hence this mode was chosen since OPS-SAT uses the 437 MHz amateur radio band for downlink. The transceiver is capable of better transmission modes with improved synchronization e.g., mode 5 uses a 32-bit Attached Synchronization Marker (ASM). However, this was not changed to stay compliant with regulations.

Distinguishing objects from a multiple launch added to communications problem

As is often the case with rideshare launches, OPS-SAT was separated with multiple spacecraft in quick succession. The LEOP plan called for the enabling of the GPS receiver to perform an independent orbit determination from which a TLE could be derived. However, given the on-going communication problems this was not possible, so external TLEs had to be relied on. As there were multiple objects in about the same orbit it became increasingly difficult to distinguish if bad communications were due to poor link quality or because the ground segment was pointing at the wrong object. The ground stations were also not equipped with the functionality to introduce a positive or negative time overset value which would have helped in this investigation. Finally, this was resolved by coordinating with the ANGELS and EYESAT operational teams to find out when they were transmitting in S band. With this information those satellites were identified using ESOC-1 and this helped to locate OPS-SAT.

S band communications are impacted by an OBSW bug

Since the UHF communications were unreliable, it was decided to switch to S band. At the first attempt the S band transmitter did not come on. Analysis revealed that there was an OBSW bug causing the software to ignore the "on" command if the unit was already powered on but not transmitting. Since the automatic system had already placed the system in this state, it was decided to turn on the transmitter by direct I2C command. This route had the disadvantage that the automatic software FDIR to switch off the transmitter after 12 minutes would not get activated. Hence multiple procedures to switch off the S band transmitter in different ways were prepared before the pass. The S band transmitter was commanded on successfully using the direct I2C command and telemetry was successfully received. However, it could not be commanded off, even by direct I2C command. This was a critical situation, as the S band transmitter had no hardware temperature monitoring FDIR and the maximum on-time recommended by the provider was limited to 15 minutes. Towards the end of the pass, it was successfully turned off using a direct command to the power switches sent via UHF. Analysis revealed that an OBSW was preventing the off command from working correctly and a full OBSW update was required to correct it. This update would have to take place in UHF despite the unreliable link.

MAJOR COMMUNICATION CHALLENGES DURING COMMISSIONING

Once the LEOP was complete the hope was to update the OBSW and move to S band high speed communications as soon as possible and then start with the challenging commissioning procedures. However, more issues arose.

S band RX noise level increased when S band TX was ON

Once the safety issues with the S band TX were resolved, an additional communication problem was discovered. The S band receiver noise level increase by 10dB whenever the S band TX was on. Industry investigation tracked it down to a radiated disturbance originating from the 3dB coupler. This had not been observed during testing. There was no workaround identified for a unit in orbit.

ESOC-1 High Power Amplifier failure

In early January 2020 one of the two SSPAs failed on ESOC-1. This reduced the effective uplink power in S band by around 5-6 dB. Since ESOC-1 had been procured as a low-cost project there were no SSPA spares available and the lead time for ordering a new one was six months. In fact, this was further complicated by the onset of the COVID-19 pandemic which meant that the SSPA was not fixed until September.

The 10 dB increase in noise level on the receiver combined with the 6dB loss of uplink power at ESOC-1 meant that the on-board receiver was not able to lock during most S band communication passes. To make matters worse, the antenna pattern of the S band antenna was highly irregular and although the spin rates were not high, a fixed attitude had not yet been achieved. This meant it was not possible to predict when (and if) high speed duplex communications would be possible as it required a particular attitude between the spacecraft and the ground station to be achieved due to the severely degraded link.

Unexpected spin-up of the satellite

A gradual spin-up of the spacecraft started to be observed on February 22, 2020 (1 deg/day). Initially this could not be explained as the spacecraft had been in BDOT mode (magnetic rate reduction) since the first day of the LEOP and very stable slow spin rates had been observed up until that time. The spacecraft had also been without attitude control for one week during the initial OBSW load and no significant increase in spin rates had been observed. No hardware or software had been changed in the meantime. See Figure 4.

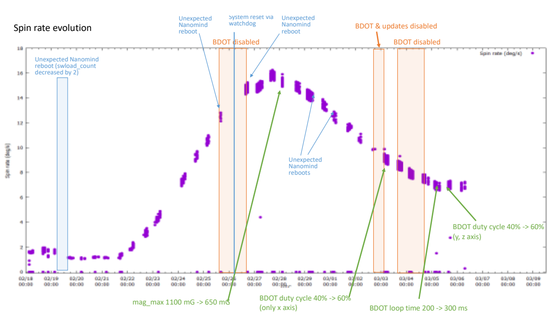

Figure 4: OPS-SAT spin-up history.

Once it approached 15 deg/day the FCT tried regularly switching the BDOT mode on and off with timetagged commands in an attempt to try and stop the spin-up but this had little impact. Following an unexpected reboot of the NanoMind the rate started decreasing but a test to observe what would happen if BDOT was deactivated completely proved that the rate still came down regardless. A tiger team was established at ESOC to help find the root cause. A swap over from NanoMind 1 to NanoMind 2 was made to eliminate the possibility of a hardware fault. There was no impact, hence the attention was switched to software. An analysis from ESTEC also revealed that it was quite possible that the cause of the spin up (and down) was a periodic resonance between the spin angle/rate and the residual magnetic field being generated by the solar arrays as they were exposed to sun and then shadow during rotation. Simulations by ESTEC projected an eventual uncontrolled and unbounded increase in rotational energy, thus time was limited.

Attention was put on the BDOT functionality itself. Analysis with industry uncovered that there was an I2C timeout condition under which the control loop would stop without it being directly telemetered back to the higher ADCS mode that was being monitored by the FCT. Monitoring of the low level "looptime" i.e., how much time was spent in a single loop of the BDOT controller, proved critical in establishing that failed acquisitions of the fine sun sensor and long loop times were correlated.

On March 12, 2020, it was decided to disable the FSS acquisitions and reenable BDOT during a pass. Again, no impact on the rates could be seen and it was decided to leave BDOT activated and see how the system reacted overnight. Due to the low-cost nature of the mission, late evening and morning passes were taken automatically. Luckily on this evening a member of the FCT checked the rates at home after the final pass. They had increased to 30 deg/sec. To put this into perspective an estimate of 40 deg/sec was determined unrecoverable given the ongoing communication problems. The FCT and TU Graz took the first morning pass manually and managed to reboot the OBSW via UHF. This stopped BDOT. The rates had reached 60 deg/sec but it was still possible to get some commands on-board via UHF. Further investigations followed on how the spin-up could have occurred. Finally, a GOMSpace engineer found an inconsistency in the wiring between NanoMind2 and the Magnetorquers on a photo that TU Graz had taken during integration. This error was not present on the flatsat or NanoMind1. This sign error was relatively easy to correct in a configuration table and BDOT was entered again. This time it worked in the correct direction and successfully brought down the spin rates.

OVERCOMING THE CHALLENGES

Even though the situation looked bleak at times, there were positive aspects. Firstly, OPS-SAT had been designed with multiple access routes in mind, including being compatible with the Radio Amateur community. None of these communication routes were good enough to perform commissioning on their own but they could be combined. Another unique aspect of OPS-SAT was the existence of a very powerful processor capable of running open-source software, connected to the ground via a high-speed file transfer link. However, to exploit these opportunities the FCT would have to operate completely out of the box from traditional operations concepts.

Use of Radio Amateur support and the SatNOGS network

Given the extremely bad communications in UHF at the start of the mission and the safety issues with S band, it was effectively impossible to make progress once the initial basic LEOP goals had been achieved. However, ESA had ensured that Radio Amateurs worldwide had been informed of the launch and had distributed all the necessary software and information for decoding the UHF beacons. This meant that a considerable number of Radio Amateurs were taking OPS-SAT passes and the raw packet data, decoded beacon and waterfall information was often available via a network called SatNOGS. The FCT learnt very quickly to integrate this information into the operational concept. For example, the beacons contained a counter for the number of commands received so the same command could be sent multiple times and then the counter checked if it had increased from a beacon received on SatNOGs. Even the waterfalls began to give useful information on spin rate as the oscillating signal strength was clearly visible and strongly correlated. After a few weeks this was taken a step further and a pipeline was built that would automatically retrieve raw packet data from the SatNOGS website and decode it using the Mission Control System Database. This effectively provided the FCT with spacecraft telemetry on a 24/24, near real-time, basis. Of course, operating in such a fashion was very slow but progress could and was made in platform commissioning.

Mixing the bands

As the quality of the UHF link improved more packets were received but still the uplink was very unreliable. However, reliably commanding in S band was still possible. The operational setup was changed so that the mission could benefit from both, in parallel. The classic setup had been to use the prime MCS chain for S band operations and the redundant MCS chain for UHF operations. It should be noted that the actual packets sent between the OBSW and the MCS were identical and did not depend on which route they took to the spacecraft or to the ground, only the physical, data link and network layer were different. The system was modified to allow the FCT to send commands in S band on the prime MCS chain but to receive the packets in UHF. This mode was termed “Hybrid.” This was a further improvement on the SatNOGs solution and progress accelerated. It was successfully used over the course of a week to perform the first OBSW update. The update was achieved by sending some 5,000 telecommands, each of which wrote 200 bytes to a file which could be verified via checksum prior to booting.

Use of SEPP as an OBSW update tool

After two complete OBSW updates the FCT finally felt confident enough to use the S band link in duplex mode. However, bit locks were rare due to the problem of the radiated disturbance originating from the 3dB coupler and the SSPA failure on ESOC-1. Hence, the hybrid mode was still used for these loads. ESA/ESOC took the lead on the OBSW development in spring 2020 to accelerate progress on the commissioning and complete OBSW updates were made at an average rate of once every three weeks. These operations were consuming a significant number of the operational passes. Progress had been made in other areas of the payload commissioning, especially on the SEPP and the CFDP-based file transfer technique used to communicate with it. One member of the FCT pioneered a process that loaded the OBSW to the SEPP instead of to the target NanoMind. The advantage was that SEPP software could accept the commands at a much higher rate than the NanoMind software. Also, the OBSW binary file could be compressed for uplink and then decompressed on-board. This meant that the file could be loaded to the SEPP in less than two minutes using CFDP compared to two hours to the NanoMind in the traditional fashion.

However, the problem now was how to get the information from the SEPP to the NanoMind. It was known that the NanoMind had an interface that was used by industry to connect to the Software Validation Facility (SVF) during testing. A SEPP application was developed that mimicked the SVF and could connect to the NanoMind and “trick” it into thinking that it was still in the clean room and being commanded by the SVF. The SEPP application split the loaded OBSW image file into the required 5,000 commands and transferred them to the OBSW over this interface. It was even capable of automatically resending commands if no acknowledgement was received. The advantage was that this could all take place outside ground coverage. Once this system was in place, it was possible to load a new OBSW file to the SEPP and program the transfer to the NanoMind in a couple of hours — all automatically — thus releasing operational time to focus on other areas.

Use of SEPP/FMS/SpaceShell as a commissioning tool

Until the ESOC-1 SSPA was repaired in October 2020, the ability to command in S band with high-speed TM enabled was extremely limited. It was not possible to know when a commanding opportunity might arise or how long it would last. This meant that most of the commissioning procedures, which were based on real-time commanding of the payloads via the NanoMind, could not be run as planned.

In response, the FCT changed the operational concept. Once the SEPP and CFDP file transfer was commissioned it was decided to run commissioning procedures automatically using Python scripts on the SEPP. In fact, this was the foreseen experimental configuration in which software running on the SEPP could control the mission. Python scripts that mimicked flight procedures (logic, check telemetry values, send commands, load configuration values from a file etc.) were developed and tested on the flatsat. They were wrapped into deployment package files called IPKs and given an experiment number. These were then automatically loaded up to the SEPP as soon as a commanding window opened. IPKs could then be installed via Linux SpaceShell. The installed experiment/procedure could be triggered by a timetag command on the NanoMind or directly via the NanoSat MO Framework (NMF) [6, 7, 8]. The artifacts produced e.g., logs or images, were compressed and downlinked to the ground during ground station passes using CFDP. The combined use of the SEPP, CFDP and SpaceShell made it possible to commission most of the payload even though the total commanding window was limited to approximately 2 minutes per day.

Commissioning the on-board camera is a good example of the flexibility of using open-source software on the SEPP. At the time, unreliable control problems with the spacecraft resulted in a disproportionate number of bad images acquired in the form of black space, over-exposed, and blurry pictures. These pictures took up significant communication bandwidth during passes and consumed FCT resources to manually sort through. An Artificial Intelligence (AI) image classifier called the SmartCam was thus developed and uplinked as an app so that only interesting pictures would be kept for downlink. The app was built using industry standard open-source technology for Machine Learning (ML) by training an image classification Convolutional Neural Network (CNN) model on the ground using thus far downlinked thumbnails as training data. The app was built on top of the TensorFlow framework which has spearheaded countless innovations in terrestrial applications of AI with easy modeling and intuitive high-level APIs. A powerful and versatile framework originally developed for terrestrial embedded systems and with strong industry heritage had thus been successfully re-used on the SEPP with little effort required. This allowed for rapid prototyping and development so that a solution was conceived, developed, tested, uplinked, and operating on the spacecraft within a timespan of less than two weeks. The SmartCam has since incorporated more open-source technologies, notably with the GEOS Geometry Engine library to develop geospatial capabilities, so that it can autonomously capture pictures when the spacecraft is above areas of interest. The need for operators to plan and schedule image acquisition operations has been eliminated, making OPS-SAT the first ESA flying mission that uses AI for planning and scheduling autonomy [9].

Remaining issues in inertial pointing are investigated by an experiment on refined astrometry to assess the spacecraft's attitude stability based on on-board analysis of images of the sky. The findings are fundamental in assessing possible improvements in sensors alignments, operations, and on-board systems [10, 11].

CONCLUSIONS

The OPS-SAT LEOP and commissioning was a challenging time. Although the spacecraft is only a 3U CubeSat it is extremely complex in terms of interfaces and configurability. Commissioning such a spacecraft while suffering from numerous communication problems required a complete rethink of the planned mission concept. The FCT had to think out of the box many times and make incremental improvements. Perhaps the most fundamental was the realization that under such communication conditions using the payload computer to run procedures normally allocated to the ground turned out to be a very effective solution (e.g., OBSW upload or commissioning other payloads). The FCT benefited enormously from the ability to install "normal" software, usually open-source, on the SEPP instead of writing custom code on an embedded system. In some cases, efficiencies were reached that were much higher than if the FCT operated a perfect satellite and followed traditional operational approaches.

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APPENDIX

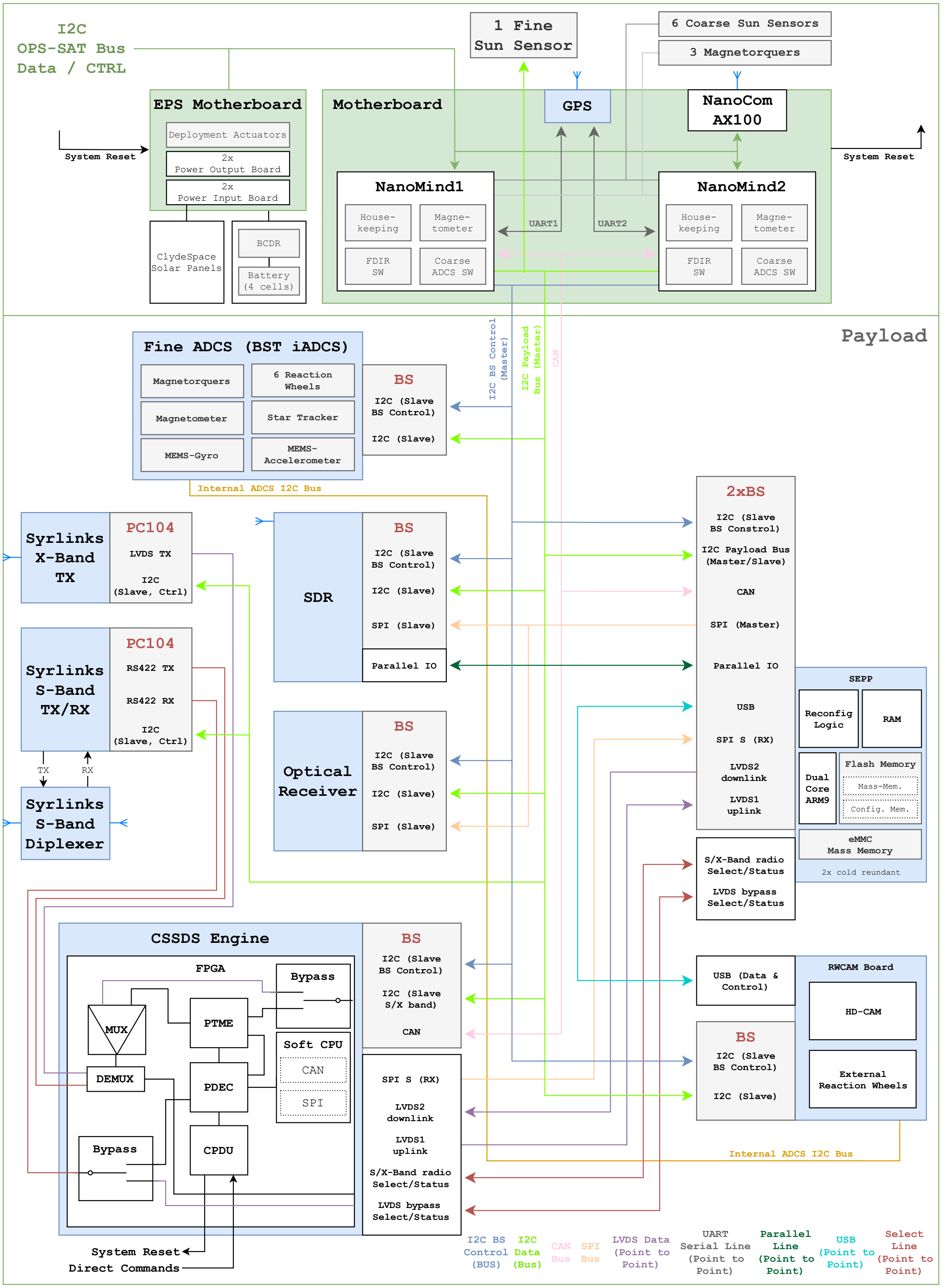

Figure 5: Space Segment System Diagram.