OPS-SAT-2: An ESA in-orbit laboratory for optical and quantum Ground-Space experimentation

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Abstract

This paper presents the ESA OPS-SAT-2 mission proposal currently within the ARTES 4.0 Strategic Programme Line "Optical Communication – ScyLight". The mission will follow the OPS-SAT Space Lab concept i.e. launching a series of powerful, reconfigurable flying laboratories for in-flight experimentation not possible, or desirable, on other missions. In-flight experience can be gained very rapidly to ensure that potential future technology works in all operational scenarios (including "on the edge" situations) before it is too late, or too costly, to modify it. Operational experience is gained naturally but due to the healthy risk aversion of operators, it can take decades to complete. OPS-SAT missions accelerate this process. Using a special design and operational expertise, ESA assumes the risk of executing these experiments, thereby releasing industry to concentrate on completing de-risking activities as fast and cost effectively as possible. Each mission concentrates on a different field where the need for rapidly gaining operational experience has been identified.

Keywords: OPS-SAT Space Lab, OPS-SAT-1, OPS-SAT-2, Optical Communication, ESA

Acronyms/Abbreviations

CDF – Concurrent Design Facility
DPU – Data processing unit
FCT – Flight Control Team
NMF – NanoSat MO Framework
SNN – Spiking Neural Networks
VM – Virtual Machine

1. Introduction

OPS-SAT Space Lab is a concept of the European Space Agency (ESA) designed to demonstrate the capabilities of cutting-edge satellite and ground control software under real-flight conditions. The first effort of this concept, OPS-SAT-1, is being led by the European Space Operations Centre (ESOC) in Germany and is a pioneer in its field globally. This paper highlights the three successful years of operations of OPS-SAT-1 and introduces the follow-up effort, OPS-SAT-2, which will continue the same concept of launching a fleet of powerful and reconfigurable flying laboratories for in-flight experimentation.

The main objective of the project is to allow industry to concentrate on de-risking activities efficiently and cost-effectively while ESA assumes the risk of executing the experiments by utilising a special design and its operational expertise. Each effort will concentrate on different areas where the need for rapid operational experience has been identified. The paper provides a comprehensive overview of the current and planned efforts of the OPS-SAT Space Lab fleet, including detailed information about OPS-SAT-1, its achievements, and the experiments it has conducted.

The paper also delves into the lessons learned and potential improvements that will influence the design of future efforts. An in-depth analysis the lesson learned, and potential improvements which will flow into the development of future projects can be found in Section 4 of the paper. The next effort, OPS-SAT-2, which is currently under development, is introduced in Section 5 of the paper. The conclusion, Section 6, summarizes the key findings and future work, highlighting the significance of the OPS-SAT Space Lab project for the field of space operations.

2. OPS-SAT-1 General Information

OPS-SAT-1 is a significant milestone in the series of missions designed to serve as testbeds for cutting-edge technologies, applications, techniques, and methods of operation by the European industry, education institutions, and research organizations. It is the first nanosatellite owned and operated by the European Space Agency (ESA). It was launched in 2019 and has completed three successful years of operations in low earth orbit. The primary objective of OPS-SAT-1 is to evaluate the application-level protocols developed for ground-space communications that have never been tested in flight before. Moreover, the satellite provides a platform which has already been used for over 230 experiments. These experiments were conducted by a diverse range of experimenters, including space agencies, major primes, new space entrants, and university research groups. They cover a wide range of topics, such as image processing with machine learning [4,11], compression [3,12], software-defined radio [6,7], and attitude control [5]. The success of OPS-SAT-1 validates the viability of the concept and serves as the foundation for future missions in the OPS-SAT Space Lab series.

2.1 Space Segment

All OPS-SAT satellites follow a basic design which is necessary to allow open experimentation. OPS-SAT-1 is a good example as the nanosatellite can be considered as comprising of two satellite systems integrated into a single frame. The traditional system, entirely autonomous and powered by the Nanomind computer, is responsible for controlling critical components, as well as managing and monitoring the Satellite Experimental Processing Platform (SEPP). Both the Nanomind and SEPP are equipped with redundancy, each featuring two units, with only one powered at a time. The SEPP, being the heart of operations, serves as the primary platform for conducting experiments. It is equipped with an ALTERA Cyclone V System-on-Chip (SoC) featuring an 800 MHz dual-core ARM CPU and 1GB DDR3 memory, making it one of the most powerful active systems in orbit. The SoC also includes an FPGA module that can be reconfigured for experiments as required.

OPS-SAT-1 is equipped with two Attitude Determination and Control Systems (ADCS), with the coarse ADCS being utilized by the On-Board Software (OBSW) for spin rate monitoring and the fine ADCS being utilized by payloads for active pointing and experiments. The system features magnetometers, gyroscopes, a star tracker, photodiodes for attitude detection, magnetorquers, and reaction wheels for attitude control. Communications are available in UHF and S-band for both uplink and downlink, as well as X-band downlink and an optical receiver. The satellite also provides access to a software-defined radio and a camera for experimenters. The complete diagram of the OPS-SAT-1 space segment is presented in Appendix 1.

2.2 Ground Segment and Space-Ground Communication

The ground segment of OPS-SAT Space Lab is centred around the European Mission Control Software, SCOS, which has been modified to handle the new application-level interface CCSDS MO Services [2]. The mission software is hosted on VMs in the ESA SMILE servers and includes various instances of a Mission Control System for testing, operations, real-time command and control of antennas, experimenter access, and data processing. The ground segment is located and the operations are conducted in the European Space Operations Centre (ESOC) in Darmstadt.

OPS-SAT-1 utilizes three ground stations, two of which are provided as part of the SMILE facilities [9]. Most of the spacecraft operations are conducted in the S band and include mission planning, experimental operations, uploading and downloading of files. The mission uses a single SMILE S/X band ESOC-1 station, which features a 3.7-meter single parabolic reflector and supports S band up and downlinks and X band downlinks, with a maximum angular velocity of 10 degrees per second in a three-axis system.

The mission also relies on two UHF ground stations; one at ESOC called ESOC-2 and the other at the Technical University of Graz in Austria. The UHF connection was the primary communication channel during the launch and early commissioning phases, but currently serves as a secondary channel primarily used for troubleshooting during on-board anomalies.

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. The underlying transport protocol is MO packets on top of CCSDS framing. Additional protocols, including CFDP, TCP/IP, and basic Linux shell access (known as SpaceShell), are available for commanding the SEPP over the S band link. File-based operations are extensively used when communicating with the SEPP, especially when loading experiments, software, firmware patches, and downloading experiment results. A diagram of the interactions between the ground and space systems can be found in Appendix 2.

2.3 Experimenter Satellite Access

OPS-SAT-1 offers experimenters various means to transmit and receive data to and from their applications running on the satellite. Fig. 1 illustrates the various options available. Experimenters can interact with their NanoSat MO Framework (NMF) application through a comprehensive Mission Control System (MCS) interface accessible through a web browser. The MCS provides advanced capabilities typically found in ESA Mission Control Systems, including activity tracking (TCV), modifying parameters, aggregation control and view, and message display.

Additionally, experimenters can prepare command stacks in the form of XML files and upload them to the ESA LWMCS server, after which they can connect through port forwarding and access a web page. A full-duplex data link with the on-board application is established via a Space Packet Protocol (SPP) stream exposed via a socket, which experimenters can connect to over the internet through an SSH port forwarding. Each experimenter is assigned a unique Application Identifier (APID), which is used to route the packets on board via the Controller Area Network (CAN) bus to the SEPP. Experimenters are free to define the payload of the Space Packets. The connection between the ground segment in ESOC and the experimenter is encrypted using an SSH tunnel and appropriate cipher usage. The SPPs are uplinked to the satellite and sent on board the CAN-bus through the TMTC encoder/decoder using the CAN Fragmentation Protocol (CFP). The SEPP, which is connected to the CAN-bus, reassembles the CFP messages into SPP packets and delivers them via a TCP server port. In turn, experiments can connect to this port and receive a stream of unfiltered Space Packets and transmit them to the ground.

Experimenters can use SFTP to exchange files with their experiment. This can range from uploading time-tagged schedule files to downloading logfiles and images. Experimenters can simply drag and drop files into an SFTP folder hosted by ESOC, which is synchronised with the respective folders on the satellite. The experimenter will receive a notification through a logfile once the operation is complete.

A binary executable for different operating systems is also provided to experimenters, which they can use to open a command shell to their designated location on the satellite. This mechanism leverages the same SPP stream exchange.

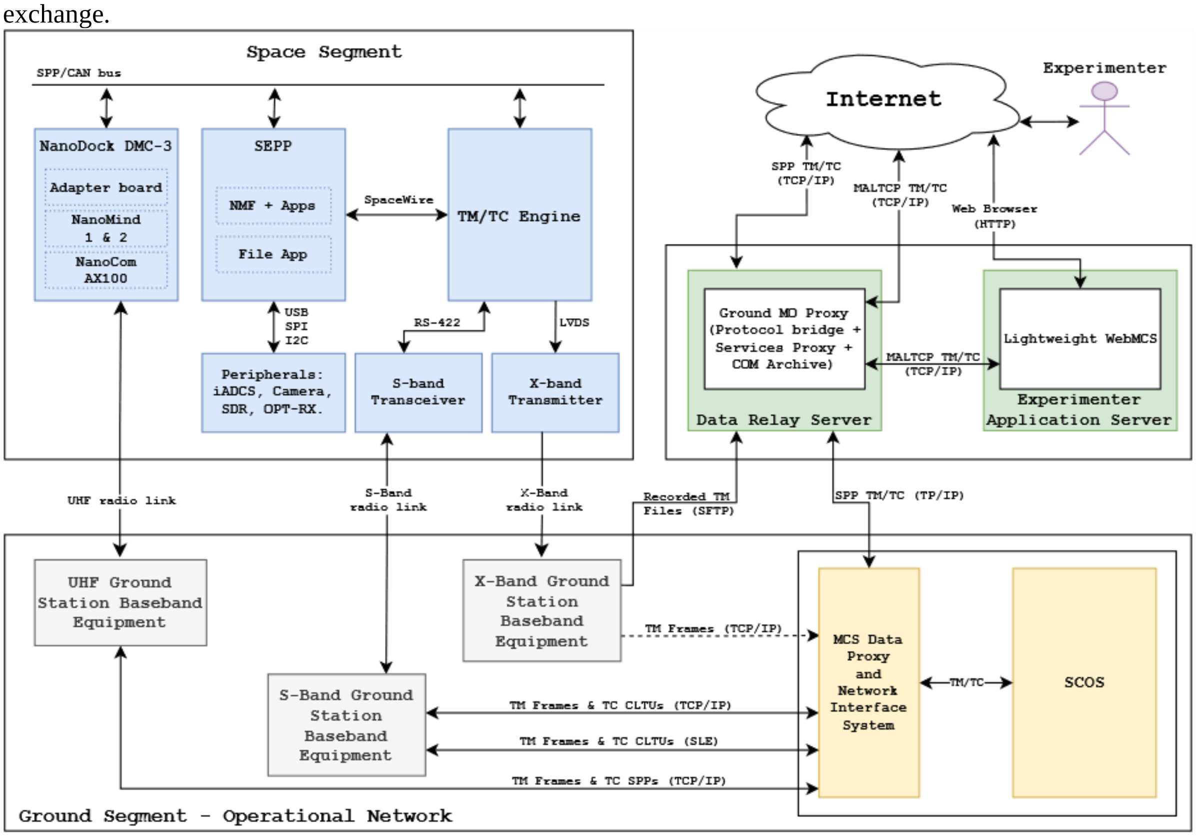


Fig. 1. Experimenter satellite access routes.

3. OPS-SAT-1 Experiments and Achievements

3.1 Overview of the Experiments

Over three years more than 230 different experiments were developed and executed by OPS-SAT Space Lab on-board OPS-SAT-1. Over 60 papers have been published on the experiment results: conference and academic publications, scientific articles, and presentations [10]. Most of the experiments were carried out by the external organisations, but also the OPS-SAT Mission Control Team engineers have implemented and executed several successful experiments. In some cases, an internal experiment was successfully continued by an external organisation, thus building on top of successful implementations. SmartCam listed below is a good example of such cooperation. Below are some examples of internal and external experiments done on OPS-SAT-1 satellite.

The OPS-SAT Space Lab team has produced the following experiments:

- SmartCam [4] is a tensor flow-based machine learning experiment that sorts the images taken by camera on board and makes it easy to decide which ones to download, saving downlink bandwidth. This experiment can also be used as a baseline to connect further machine learning experiments.
- Packetstore is a simple data collection experiment that allows the MCT to store large amount of telemetry in the form of files on the experiment platform, instead of storing them on the platform on-board computer. This gives an operational advantage, as file downloads are faster and are less affected by data loss.
- OrbitAI experiment [11] performs Machine Learning (ML) training as an autonomous in-flight operation. Running on-board, the experiment uses online ML algorithms to train fault detection, isolation, and recovery (FDIR) models that can be used to protect the on-board camera's lens against exposure to sunlight.
- GNU Radio Based Search and Rescue demonstrates [6,7] the design of a software configurable Search and Rescue receiver using GNU Radio, running on Linux in a 3U CubeSat. The system can autonomously detect and decode transmissions from terrestrial 406 MHz beacons from the global COSPAS-SARSAT search and rescue system.
- POCKET+ [3] method, referring to a method for losslessly compressing a sequence of fixed length input binary vectors into a sequence of variable-length output binary vectors rather than specifying packets. For instance, this could be applied to images where the fixed length is the width. The algorithm imposes no requirements on the format of the input data except that the input vectors must be of fixed length.

Here are some highlights of experiments, implemented and executed by external organisations:

- FAPEC [12] a high-performance and versatile data compression software. Among others, it features image compression and linear prediction coding algorithms, suitable for multi-band and baseband radio frequency (RF) samples, respectively.
- Angle-based Correlation [AbC] method [5,16] is a full process combining linear estimate optimization and quaternion algebra. It reviews the possible errors in the chain of measurements. Then computes an estimate of the beacon location and its covariance in the focal plane. Then transforms this image location into an absolute direction of the sky by reversing the gnomonic projection, which first requires a fine re-centering and rotation of the image against the sky.
- SPiking Low-power Event-based ArchiTecture (SPLEAT) [13] for SNN's hardware deployment. Equipped with a modular structure and time-multiplexed structure, SPLEAT allows integrating a variable number of modules representing SNN layers. Therefore, SPLEAT has the ability to support a wide range of deep and convolutional SNN topologies. In addition, it has an event-based structure that fits conveniently with the spiking data behavioural characteristics.
- Stock exchange [14] in space – software was deployed with a stock-exchange server to improve the reliability, storage efficiency, communication, and security of financial transactions.
- Anomaly Report Tracking System (ARTS) [15] enables the identification of the root cause of an anomaly event and predicts its likelihood of occurrence in the future. However, traditional manual tracking and analysis of anomalies has limitations. Simple out-of-limit checks are not capable of detecting subtle anomalies and identifying abnormal behaviour requires expertise in the relevant field, thus requiring mission experts to be readily available.

3.2 OPS-SAT-1 Firsts

Recently, in January 2023 the Mission Control Team has gone through the list of successful experiments and dedicated publications summarizing a list of "firsts" – activities that OPS-SAT-1 has pioneered:

- first ever space mission dedicated to operational technology
- first nanosatellite directly owned and operated by ESA
- first ever in-orbit laboratory where the public can load and test software/firmware
- first ESA mission directly controllable in real-time over the internet by the public
- first ESA mission to reconfigure an in-orbit FPGA on a daily basis
- first ESA mission to use CFDP (CCSDS File Delivery Protocol) operationally
- first ESA mission to use fully MO-based on-board software and ground implementations
- first ever stock market transaction successfully performed in space
- first European deep learning processing of an image using an on-board FPGA
- first on-board update of an ANN (artificial neural network) in space in an institutional mission
- first successful in-orbit decoding and processing of ground based emergency beacons
- first successful re-training of an on-board AI model with live in-flight data
- first successful loading and in-orbit operational use of an AI model for FDIR
- first successful in-orbit implementation of a Spacewire protocol on top of an existing LVDS connection
- first mission successfully commanded with Europe's next-generation mission control system EGS-CC.

The list is presented in the OPS-SAT Experimenters' Community Portal [8], the exact links for each of these points are available on the webpage.

3.3 OPS-SAT Space Lab: How to become an experimenter

OPS-SAT is open for any ESA member state (including Canada) organization - industry, institutions, research groups - for running their experiments in space at no cost to them and minimal bureaucracy. The process to become an experimenter is very simple and fast and will be for the future missions as the currently flying OPS-SAT-1. The process description is available on the OPS-SAT Experimenters' Community Platform [17], and also described here:

1. Contact OPS-SAT Space Lab via ops-sat-experimenter-support@esa.int to discuss the feasibility
   If declared feasible:
2. Fill out the experimenter form to be registered by the OPS-SAT experimenter support and receive access to:
   - the experimenter portal containing detailed technical documentation, available software, example projects, wiki, lessons learnt etc.
   - the experimenter community (synergies between experimenters are encouraged)
   - your own unique directory on the spacecraft for storing software/firmware/results
3. The experiments are incrementally developed and different versions are submitted for testing via an automatic check and build pipeline
4. The lab tests the experiments on a series of testbeds, each with an increasing level of sophistication. *A fast feedback loop with the experimenters is started and finishes when it is declared to be flight ready.
5. The experiment is loaded onto the spacecraft and executed. Another fast feedback loop of in-flight execution and experiment improvements is started. ESA handles the risk allowing the experimenters to concentrate on generating value.

The record so far: the shortest time from initial contact to the delivery of the results of the successful execution to the experimenter is 72 hours.

4. OPS-SAT-1 Lessons Learned

Due to the experimental nature of the mission and the goal to break the "has not flown, will not fly" cycle, the mission has experienced several major challenges both before and after the launch, especially during LEOP and commissioning phases [1]. Thankfully all the challenges could be successfully overcome by the Mission Control Team (MCT). These challenges have led to a list of valuable lessons and potential improvements for future missions. This complete list currently includes 265 points and have been distributed within ESA. Some of these lessons include:

- Emphasizing interface redundancy over module redundancy can provide better protection against hardware failure and improve system reliability. Especially for troubleshooting it is important to have multiple ways to communicate with each of the different subsystems on-board.
- Related to the above, deep access into subsystems can increase their functionality. An example is access to the SEPP unit from Nanomind via UART. When it was not possible to communicate to SEPP via usual channels, UART was repurposed as a communication mechanism.
- A complete and fully representative Engineering Model / FlatSat is required for proper testing. Every difference and limitation of the EM compared to the FM makes a certain activity non-testable or the test results inadequate.
- It is important to treat the hardware as if it is already aged from Day 1, as this will multiply its lifespan. A good example here is the eMMC of SEPP and Nanomind and failures in it caused presumably by hardware aging and radiation.
- All hardware combinations should be tested to identify hidden bottlenecks that could impact the entire system, such as the CAN limiting downlink or the Fine Sun Sensor limiting I2C.
- Ensure full transparency of any mechanism that does not come with support (for OPS-SAT-1 this was for example the OBSW), including logging for failures
- Support of the radio amateur community in receiving telemetry can provide a useful source of information and multiply the amount of TM received. This is especially important in case of problems with the nominal antennas or communication channels.

These lessons learned provide a valuable input for the design of future OPS-SAT Space Lab missions, as the operational concept and experimental approach will remain mostly the same.

5. Future OPS-SAT Space Lab Missions

5.1 OPS-SAT-2

OPS-SAT-2 was proposed as the second mission for OPS-SAT Space Lab and the chosen field was optical and quantum communications. Ground-Space optical links have the potential to completely disrupt many types of space missions, including Earth observation. The high data rates combined with the lack of frequency regulation mean many more ground stations can easily be deployed reducing reaction times and increasing throughput. However, there are many operational challenges that need to be overcome for these missions to reach their full potential. The need for OPS-SAT-2 was identified by space and ground system operators currently working in this area and acknowledging that there is very little operational experience yet. Besides the opportunity to fly and test hardware, the mission will contribute to mastering these operational challenges, such as how to effectively plan links under variable cloud and turbulence conditions or operational constraints operating from city centres with airports etc. It will also help to identify new market opportunities. An ESA CDF study was run in July/August 2021 to assess the feasibility of such a mission. The CDF team recommended a 12U CubeSat, which would release resources for additional payloads preferable in the optical domain. Another conclusion was that significant performance of the ADCS and GNSS subsystems was required to handle the pointing requirements of such a mission.

Whereas OPS-SAT-1 was implemented and funded under the ESA GSTP programme the Lab has started a successful collaboration with the ARTES Scylight programme for the next missions. This has resulted in a first mission called OPS-SAT Versatile Optical Lab for Telecommunications i.e. OPS-SAT VOLT. The UK Space Agency is potentially a significant funder of this mission and ran an open competition in 2021 to find a prime to lead the mission. The present favourite for the position is Croft Prospect who will provide a payload consisting of a optical terminal, quantum source, forward cloud scanner, hyperspectral camera and FPGA computer for configuring the optical terminal. They will also work on innovative updates for the backend of the optical ground stations. The platform itself (12U) is potentially supplied by Nanoavionics of Lithuania and incorporates high-performance COTS subsystems. Additionally a powerful Artificial Intelligence (LEOPARD) enabled computer with integrated FPGA will be potentially provided by KP Labs of Poland. After two years commercial operation the mission will be handed over to OPS-SAT Space Lab for experimentation by a wider community.

In terms of experimentation autonomous approaches for acquiring and re-acquiring the optical link on-board when faced with different cloud and atmospheric turbulence conditions will be validated in flight. Variable and semi-real time adaptive data rates to optimise the data rate during the pass over the optical ground station and pushing to low elevation angles will be tested. The transmission of a quantum channel together with the optical communication channel will enable the early characterisation of solar and blue-sky background and straylight issues when detecting single photons.

On the ground side, early operational testing and validation of the different optical ground stations coming on to the market will be performed. This includes portable ground stations placed in different environments such as city centres or near airports. The availability of a beacon in space will support the development and validation of models for the characterisation and understanding of optical transmission through atmospheric turbulence.

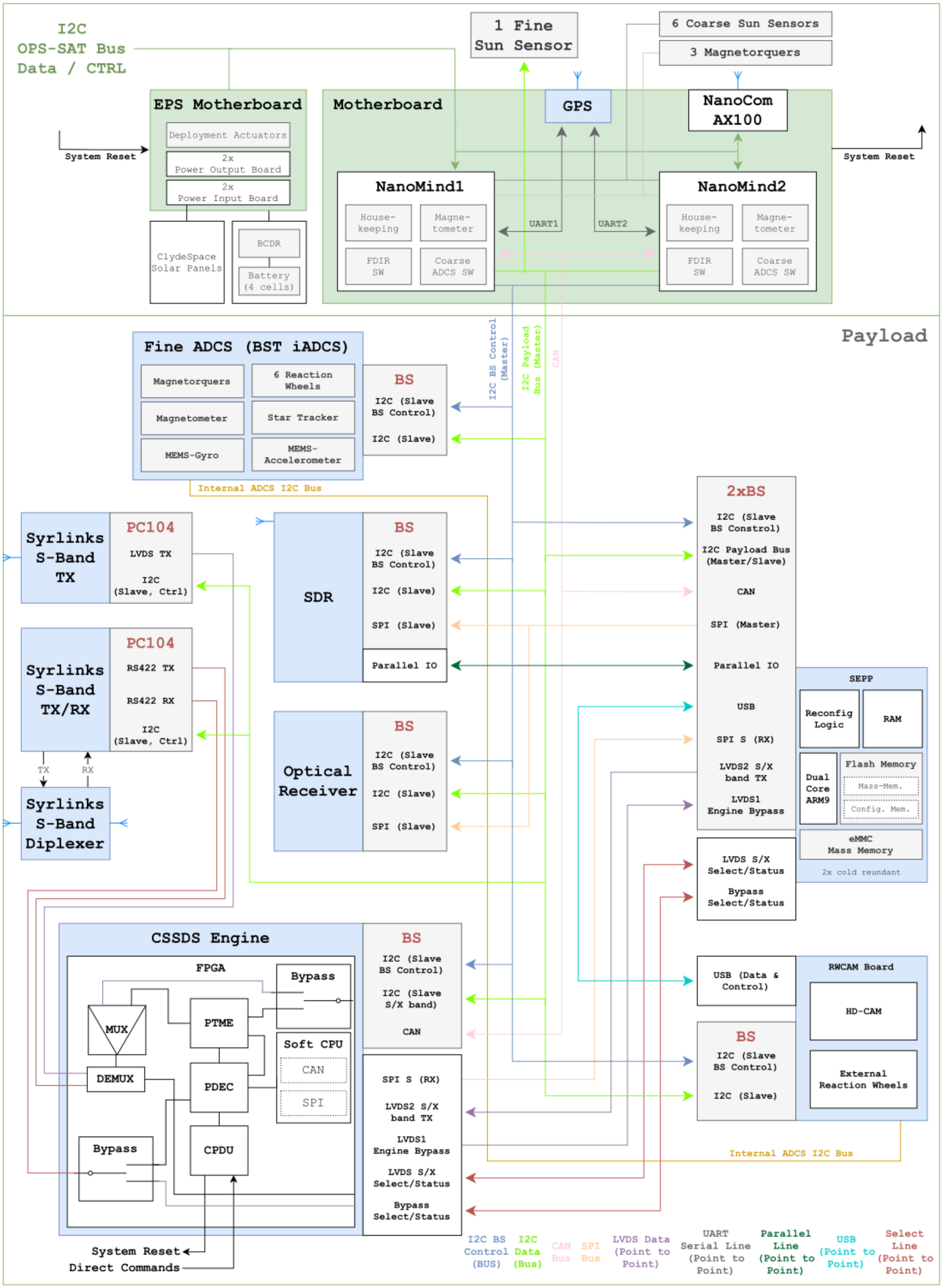
On the system side, new ways of planning optical communication links are certainly going to be required in the future and they need to be tested under real-world conditions. The variability of cloud cover over the geographical areas targeted by optical and quantum missions for their main markets means classic planning systems used in RF missions will no longer work. An autonomous, distributed, networked system with intelligent nodes on the spacecraft and the ground terminals will be required to solve this time varying problem. OPS-SAT-2's DPU will play a critical role in trying out different strategies using Machine Learning and AI.

As well as OPS-SAT VOLT, ESA ARTES Scylight intends to release a thematic call for more OPS-SAT Space Lab missions in early 2023. The technical ideas from the ESA CDF will be used to generate ideas for industry to submit their own projects in the realm of optical and quantum communications which have an ultimate destination of being available to a wider community for experimentation by European industry and academia. Successful applicants will be processed and multiple projects could be ready for kick off in late 2023.

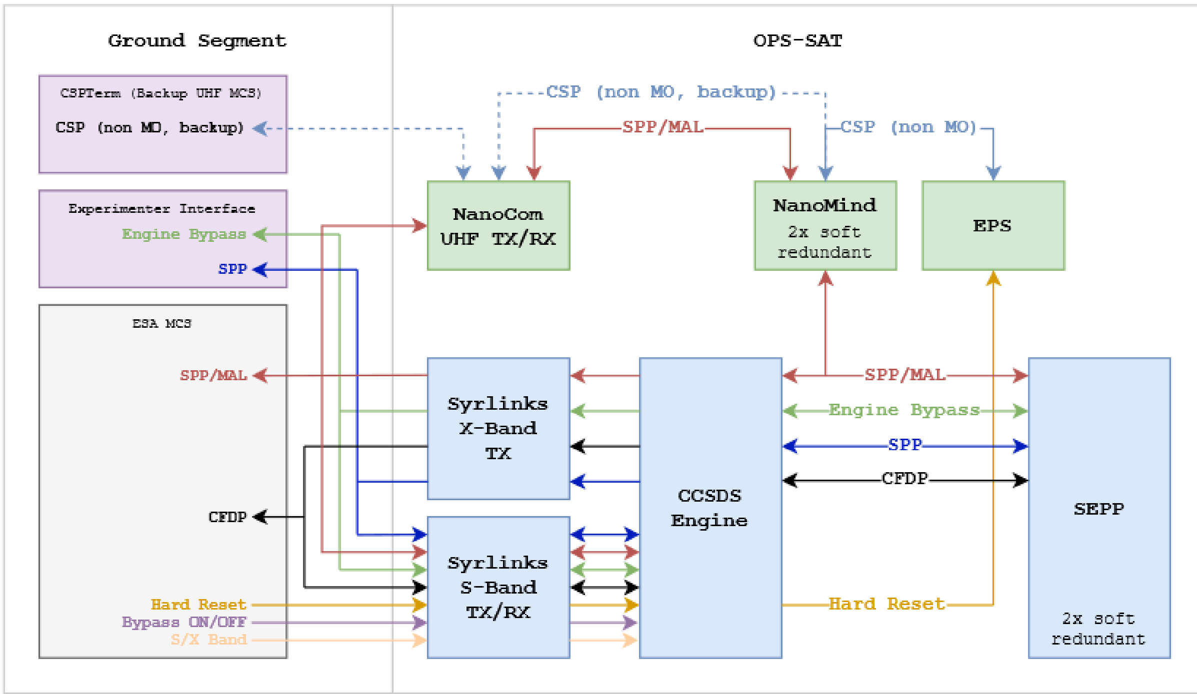
6. Conclusions

The OPS-SAT Space Lab has proven the feasibility and value of a low-cost, high reusability mission for the explicit improvement of operations and testing of new technologies in the actual operational environment over the first three years of operation with OPS-SAT-1. As OPS-SAT-1 continues supporting academia, organizations and industry, OPS-SAT-2 will expand on the offering. The available tools and instruments will push the limits of what can be tested in space, especially in the potentially game changing area of quantum and optical communications. Through future additions to the Space Lab and ever-increasing experience, the threshold for experimentation with in-flight systems on communally shared hardware will further decrease and the research community's accessibility to space will reach unprecedented highs. The value of this accessibility cannot be understated, as many obstacles can be either bypassed or supported with evidence by performing proof of concept field tests. This enables experimenters to "fail fast" and repeat fast "develop and test" cycles until they have products or concepts ready that can attract new funding both institutional and commercial. Through the experiments supported by OPS-SAT Space Lab and the experience of managing the rapid changes in configuration, requirements and loadouts, valuable lessons learnt have been already disseminated into the operations community. The aim is that this will result in the integration of new algorithms and methodologies in a much faster way than now [2].

Appendix A OPS-SAT-1 Space Segment System Diagram



Appendix B OPS-SAT-1 Space to Ground Communication Diagram



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