

OPSSAT PHASE A-B1

EXECUTIVE SUMMARY

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1. Introduction

This document is the Executive Summary for the study contract for OPSSAT Phase A-B1 as awarded to a consortium led by GomSpace Aps and comprising Villemos Solutions and GMV Germany.

The main responsibilities of each member of the consortium has been:

- GomSpace:
 - Study management and systems engineering
 - Mission and system requirements engineering
 - Detailed system design
- Villemos Solutions:
 - Mission operations concept definition
 - Experimenter ICD
- GMV Germany:
 - AOCS analysis
 - Payload of opportunity analysis
 - Flight software architecture

Work was begun in July 2013 and was planned for delivery in December 2013. Due to resource constraints ESA and GomSpace agreed to halt work between November 2013 and February 2014. Upon restart of the work in February it was agreed that the project should focus on “trouble points” in the overall design of the OPSSAT concept as identified by the parallel study led by TU Graz, which completed their work in January 2014.

The Final Presentation was held at ESOC on the 18th of July 2014 with participation from: ESA, GomSpace, Villemos Solutions, GMV, the OPSSAT experimenter community and industry interested in participating in the next phases of the program.

2. Main Study Results

The starting point of the project has been the Phase 0 study performed by ESA ending with a project review in the Concurrent Design Facility.

2.1. Mission Requirements

The consortium has prepared the Mission Requirements Document (MRD) including discussion of the mission background, mission statement, mission requirements and identification of main driving requirements and constraints.

In the MRD the mission statement is formulated as follows:

“OPSSAT shall provide an in orbit platform that through reconfigurability shall allow experimenters to uplink and execute software experiments that will advance the state-of-the-art of mission operations and have a clear potential for use in future ESA missions.”

Experimenters are entities within ESA and within the European academic and industrial community that can deliver relevant software experiments compliant with the OPSSAT capabilities.

The mission shall be realised as a nano-satellite mission leveraging cubesat COTS components where possible, without compromising a minimum life-time target of two years.”

Further a number of terms were defined to have special meaning within the OPSSAT mission context:

Software Experiments are experiments provided by the experimenters anticipated in the form of a binary image that is uplinked to the spacecraft and then deployed on the *control core*.

The **Control Core** consists of the S-band TMTC chain and the board containing the infrastructure for executing the experiments (FPGAs and control logic). All mission critical software functions are encapsulated in the control core (bus reset, software image upload, reboot to software image).

Peripherals are hardware systems that are required by the *software experiments* in need of relevant input and output capabilities, e.g. a camera. *Peripherals* interface to the *control core* directly, or indirectly through the *cubesat bus*.

The **Cubesat bus** is the main satellite platform based on cubesat COTS components; It includes an alternative TMTC link and can provide functional redundancy in case of S-band subsystem failure – allowing the *control core* to be fully controlled through the *cubesat bus*. In addition the interface to the *control core* allows the *software experiments* to access telemetry from the *cubesat bus* and command it as long as safety is conserved.

Payload(s) of opportunity are hardware systems/payloads that may add value to the experiments but is not required to fulfil the mission. Payload of opportunities will thus be selected within available margin to add as much value to the mission as possible.

2.2. Mission Operations Concept

The mission operations concept for OPSSAT is quite different from other agency missions due to a number of special mission requirements driving the design:

Requirement ID	Requirement
OS-MR-080	The OPS-SAT payload shall accept upload and verification of new software images to be executed using capabilities of OS-M-070.
	It shall be possible to configure experimental TMTC environments in parallel to the core TMTC chain and delegate control to the software experiments up to and including the channel encoding.

OS-MR-160	This shall facilitate full and open access to changing both on-board and ground side operations software, i.e. allow operations fully outside of the typical ESA paradigm (SCOS/PUS/CCDS) as long as mechanism are in place to ensure that OS-M-110 and OS-M-140 are enforced.
OS-MR-140	At any time shall OPSSAT be under exclusive control by ESA and no experiment shall be able to block ESA from controlling the satellite.
OS-MR-110	The spacecraft shall be recoverable and resettable by at least two independent communications routes in hardware and software. One shall be through a CCSDS compliant S-band transceiver and one shall be implemented through inclusion of an alternative low-data-rate radio link typical of nano-satellites. The spacecraft shall be able to communicate with the respective ground station in any orientation.
OS-MR-090	At least one configuration on board and on ground shall be representative of an ESA mission (including ground software and OBSW). ESOC assets including NGS-1 and REDU3 shall be available for the mission. The alternative data link as required by OS-M-110 shall use the NGS-1 station.
OS-MR-170	The ground segment shall process and disseminate all telemetry points in near real time. Maximum latency shall be 10 seconds from signal reception at the ground station to completion of processing within the ground segment and initiation of dissemination.

These requirements have been met with designs focusing on:

- Robust operational modes with detailed design of safe mode triggers, incl. triggers that are entirely hardware based.
- Operational concept for on-board software where a CCSDS compliant stack co-exists with a typical cubesat software stack, and where each part can receive commands routed from the other part
- A tailoring of PUS services to support required functions in the control core to perform standard operations for satellite housekeeping and operations for executing Software Experiments on the platform. This includes the capability to reconfigure the part of the software that implement the CCSDS/PUS compliant functions.

The figure below depicts the spacecraft modes and the transitions between them. Mode transitions due to nominal operations are black, purple transitions represent safe mode triggers due to spacecraft anomalies and the green transition represents transitions due to anomalies in the experimental software.

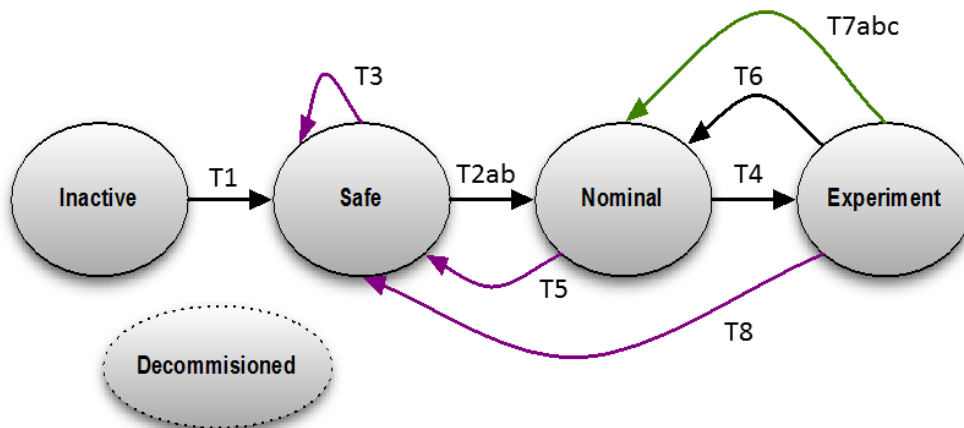


Figure 1: Overview of satellite operational modes

The sections below describe each mode and the triggers responsible for transitioning between operational modes.

1.1.1 Inactive Mode

The satellite will be in an inactive mode with all systems off during the prelaunch and launch phase of the mission. This is mandated by launch providers, and is actuated by the separation switches embedded in the structure of the CubeSat. This mode also protects the satellite by ensuring the batteries are not drained in the between deployer integration and launch. The GomSpace EPS uses a kill switch to disconnect the battery from the bus when the CubeSat is in the deployment device.

Inactive mode is also triggered by the EPS if the battery reaches a critical charge level. If this occurs, the battery and solar cells are automatically isolated from the CubeSat bus and all solar power is directed to charging the batteries. The exact critical charge level is configurable by the customer.

Inactive mode can transition to safe mode upon the physical disengagement of the kill switches built into the structure when the CubeSat is ejected from the deployer.

1.1.2 Safe Mode

Safe mode is designed to minimize system power usage while maintaining critical satellite operations in the lowest power state possible. In this mode, the EPS will cut power to all non-essential systems. In safe mode, the ADCS is set to de-tumble using the B-dot control law. TC via the UHF radio is active, along with TC via the S-Band radio. TC from the UHF radio can be relayed to the control core, and S-Band TC can be relayed to the CubeSat bus. The CCSDS engine is engaged and the UHF beacon is on.

Safe mode can transition to nominal mode by TC via either UHF or S-Band. Because every mode has initialization steps, it is possible for safe mode to re-initialize safe mode if any additional safety triggers are activated after initialization. Any full reset of the spacecraft on orbit will force the spacecraft to reboot into safe mode.

A risk in safe mode is the reaction wheels used in the BST iADSC-100. If the system is shut down unexpectedly, the wheels will spin down, imparting a torque on the spacecraft, which could cause it to tumble.

1.1.3 Nominal Mode

In nominal mode, the spacecraft is ready to receive UHF and S-Band commands from the ground station. S-Band downlink passes will be scheduled due to the high power consumption during S-Band downlink.

Nominal mode can transition to experiment mode by a TC commanding the control core to activate a deployed software experiment.

Nominal mode can degrade to safe mode if the battery charge state decreases below software defined critical levels, or if an unexpected satellite reset occurs. From safe mode, nominal mode can only be achieved via ground command on either the UHF or S-Band links.

1.1.4 Experiment Mode

Experiment mode includes all functionality which includes active use of the payloads on-board OPS-SAT, excluding the S-Band radio which may be used for normal TC/TM communication. In experiment mode, the SoMs on-board the Control core will be active as per the experiment that is deployed on the satellite.

Experiment mode can return the nominal mode by completion of the software experiment, by TC via the UHF or S-Band commanding the end of a software experiment, by a time out of a timer maintained in the Control Core, or if an anomaly is detected in the FPGA on-board the SoM. Failures that only impact the Control Core itself will only degrade the system to nominal mode. Experiment mode can degrade to safe mode if any of the safety triggers are detected.

1.1.5 Safety Triggers

There are a number of safety triggers built into the CubeSat that may force a transition to safe mode to reset systems in the event of a failure scenario on-board one of the subsystems, e.g. a SEU or malfunction of a software experiment. The full list of safety triggers is presented in the MOCD.

2.3. Satellite System Design

The satellite design builds on the results of Phase 0 and to some extent also the results from the parallel TU Graz led study that concluded ahead of this study. The following subsections highlight features of the design.

1.1.6 Payload Selection

The following introduces the selection of key parts implementing the Control Core, Peripherals and Payloads of Opportunity. Conceptually these elements are the OPSSAT Payload, while remaining systems implement the Cubesatbus.

1.1.6.1 Payload Architecture

The OPS-SAT payloads are by design decoupled from the CubeSat bus to ensure that any potential failure modes on-board payloads will not affect the core functionality of the CubeSat bus. The payloads will be able to request information from the CubeSat bus via the I2C bus, such as the output from the NovaTel GPS unit integrated with the NanoMind.

1.1.6.2 Control Core

The control core is the hardware system that will house and run the software experiments that will complete the OPS-SAT mission. The control core will consist of 4 MityARM-5CSX modules, each paired with one of 4 MicroSD cards. The MityARM SoM contains sufficient hardware capabilities to complete the software experiments of the OPS-SAT mission.

1.1.6.3 CCSDS Engine

OPS-SAT will include a CCSDS engine that will handle the framing and deframing of CCSDS packets in and out of the S-Band transceiver, as well as to the X-Band radio. The CCSDS engine will also handle routing of those packets to the appropriate bus.

The CCSDS engine will have interfaces that allow it to communicate with the CubeSat bus. The CCSDS engine will be on the I2C bus connected to all the payloads and the NanoMind. This I2C bus can be used for all telemetry and file transfer between the CCSDS engine and the NanoMind in nominal operations. There will also be a dedicated CAN bus between the CCSDS engine and the NanoMind. The CAN bus can provide a dedicated link for telemetry and file transfer to be used in the case of failure on the I2C bus. Finally, the CCSDS engine has a master kill signal line directly to the NanoPower P31us power supplies that can reset the entire spacecraft upon a ground command via the S-Band radio.

1.1.6.4 S-Band Radio

ComDev is developing an S-Band radio in a CubeSat form factor for OPS-SAT. The transceiver will be connected to the CCSDS engine with an LVDS interface for data transmission and RS422 for control. Details are to be determined.

1.1.6.5 X-band Radio

The selected X-band system is being developed by Syrlinks and based on the CNES X-band transmitter, currently in parallel development with the selected S-Band radio. The interface from the X-Band radio to the CCSDS engine should be similar to the interface of the S-Band radio. The X-band radio has two options for the data interface pins, either on the PC104 header or a discreet omnetics connector. OPS-SAT will use the discreet connector to the CCSDS engine, to reduce the pin usage on the PC104 header.

1.1.6.6 BST iADCS-100 Fine ADCS

The Berlin Space Technologies iADCS-100 ADCS unit will provide fine attitude determination with its integrated ST-200 star tracker, gyro, magnetometer, and accelerometer. It will also provide fine attitude control with the 3-axis magnetorquers and 3-axis reaction wheels integrated in the unit.

1.1.6.7 Camera

The GomSpace NanoCam C1U can provide imaging capability to OPS-SAT with unparalleled ground sample resolution for a CubeSat of 80m. The current configuration of the NanoCam 1CU is limited to 400 kbps output via I2C, which would not allow for full resolution video output. Additionally, the MCU on-board the NanoCam would likely limit the MPEG encoding speed, greatly restricting the NanoCam's ability to record video to its own storage. In its current configuration, the NanoCam could record approximately 4 frames of video at its full speed of 12fps. GomSpace could design a direct LVDS interface from the sensor to the control core, however this will require significant engineering development to implement, and the resulting system would likely no longer be considered to have flight heritage.

A second option for the camera on-board OPS-SAT is the hyperspectral camera in development by Cosine Research BV. The final configuration of this system has yet to be analysed to ensure compatibility with the current OPS-SAT system design. However, due to the mechanical constraints of the mission, it is unlikely the Cosine hyperspectral camera would fit in the CubeSat structure.

Due to the mechanical volume constraints of the mission, GomSpace proposes a third option for the camera system to minimize volume used by the system. By integrating a small camera module in a solar panel, a minimum of volume can be used by the camera while still providing space-based imagery. GomSpace recommends a camera similar in size to the Omnivision OV3642 camera, which has flight heritage on other CubeSats along with other cameras in its product series. The OV5650 is a newer module with a higher resolution of 5MP and fits in a similarly small package. An additional small camera option would be the GumStix Caspa camera module that features a Micron MT9V032 imager (seen in Figure 2). The resolution of the GumStix camera is lower than the Omnivision sensor, but the GumStix comes pre integrated in an easy to mount PCB. If a small camera module is selected, the power and data interface harness can be routed through the satellite directly to the Control Core.



Figure 2: Camera Systems: Left, GomSpace NanoCam 1CU, Right: GumStix Caspa camera module

1.1.6.8 Optical Retroreflector

An optical retroreflector can be placed on the +Z face of the spacecraft, integrated in the same panel as the small camera module. TU Graz specified a coner cube retro reflector produced by Edmund Optics that will fit in the volume available between the Control Core and the +Z panel, with the reflector itself protruding from the panel.

1.1.7 Cubesat Bus Design

The CubeSat bus is designed to use flight proven hardware in a configuration with as little risk as possible. Because the CubeSat bus is relatively isolated from the payloads on-board OPS-SAT, the bus can be designed using existing hardware with little new development. This allows for a less complex, and safer system overall.

Figure 3 describes the OPS-SAT bus architecture proposed by GomSpace. As seen in the figure, the interface between the CubeSat bus and the payloads is deliberately simple, to reduce the risk to the critical functions of the CubeSat bus. The CubeSat bus retains the capability to hardware reset the control core, allowing recovery from failures of on-board payloads. Additionally, the S-band radio can

reset the spacecraft through the CubeSat bus with the direct CAN-Bus link on the CCSDS engine. This gives the satellite redundant ground reset capability through both the UHF and S-Band transceivers.

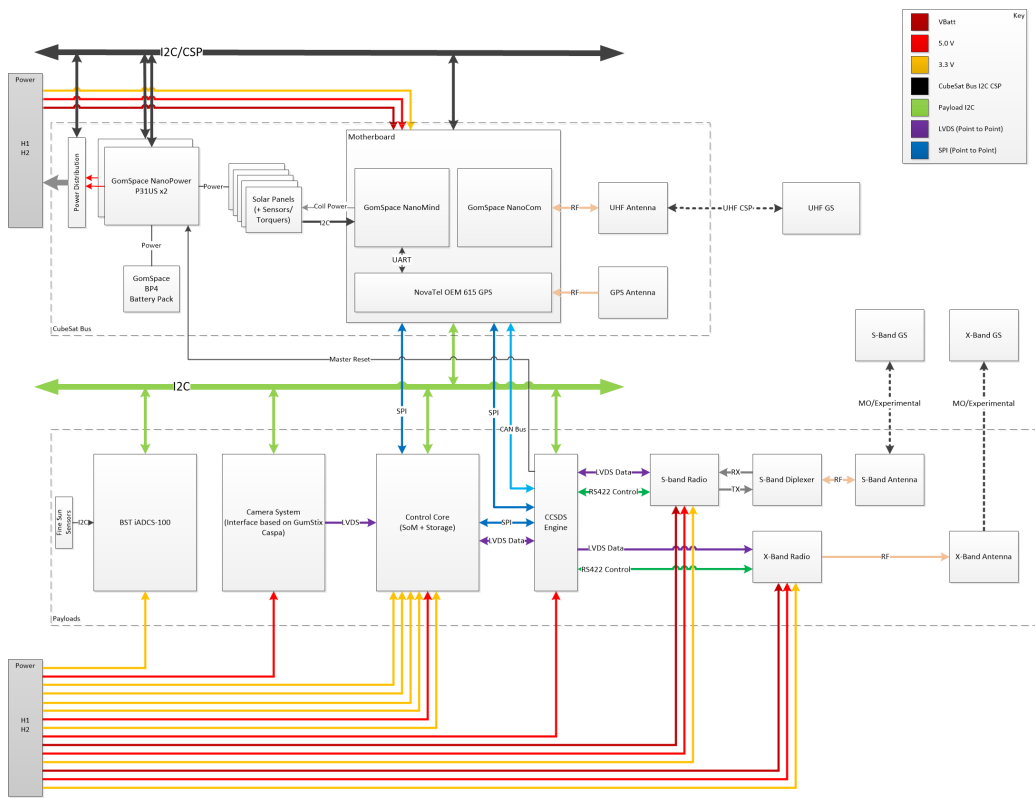


Figure 3: OPS-SAT bus architecture

1.1.8 Top Level Software Architecture

The CubeSat bus will use GomSpace CDH software and CSP for data handling, course ADCS and all critical functions. A diagram of the software architecture layout is shown in Figure 4.

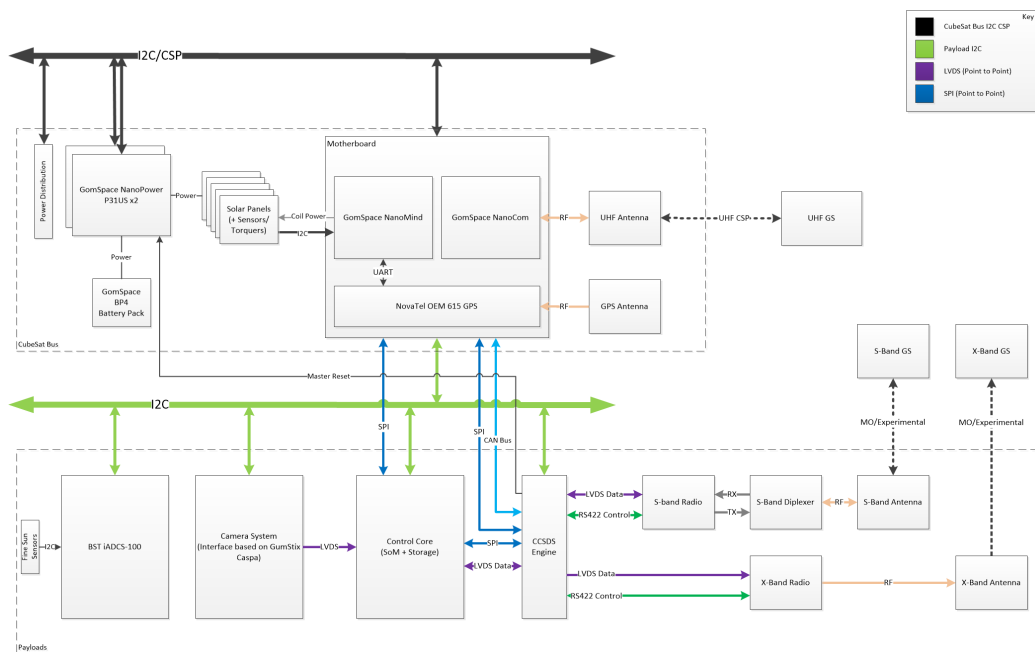


Figure 4: OPS-SAT high level software architecture

The key feature in the OPS-SAT software architecture relating to the CubeSat bus is the two I2C networks in use. The primary I2C/CSP network encompasses the NanoMind, NanoPower, NanoHub, NanoCom and the ground station. This network allows the operator and subsystems to pass CSP packets in between any 2 nodes over either the I2C or UHF links, without the need of a dedicated OBC to route the packets.

The second I2C network is the peripheral I2C network. This network is routed from the NanoMind OBC, and encompasses the BST iADCS-100, the camera system, the control core, and the CCSDS engine. Additionally, the S-Band and X-band radios can be on via the I2C network for data and control. However, it is desirable to retain the independence of the link from the S-Band radio to the NanoMind. In the baseline architecture, the peripheral I2C network should be considered vulnerable due to the presence of the control core experiments on the I2C bus. The CAN bus link from the NanoMind to the CCSDS engine gives the S-band radio an independent link to the NanoMind without relying on the peripheral I2C bus for control. All control of the S-Band radio is routed through the CCSDS engine itself via the RS422 lines. If, during the development of the S-Band radio, I2C is required, the possibility of a dedicated I2C bus between the CCSDS engine and the radio should be explored to retain the radio's independence from the peripheral I2C bus.

To accommodate the 3rd party systems on the peripheral I2C network, the peripheral network can use the default SDA and SCL pins on the PC104 connector (H1-41 and H1-43), while the GomSpace CubeSat bus uses the secondary SDA and SCL pins (H1-21 and H1-23). Because of the use of 3rd party systems where the project has little control over their PC104 pinouts, the precise pinout will need to be verified to make sure there are no conflicts on the PC104 stack connector.

A desirable design would be for all subsystems to use the CubeSat Space Protocol to communicate on the peripheral I2C network. By using CSP, the I2C bus will be significantly more fault-tolerant. CSP also allows the NanoMind to take control of the camera in the event of a failure on-board the control core, or if the operator wants to use the CubeSat Bus to take images with the camera, without the risk of having 2 systems attempting to control the camera. With the NanoCam, CSP allows native control of the camera, without needing to custom software for the I2C connection. The current revision of CSP allows the use of non-CSP slave I2C devices, such as the BST iADCS-100. This ensures compatibility of the CSP network with 3rd party systems the OPS-SAT project cannot require to use CSP.

By routing the Peripheral CSP network from the NanoMind, the CubeSat Bus is able to completely isolate the Control Core from the CubeSat Bus CSP Network. This is desirable due to the experimental nature of the Control Core software. The NanoMind will be able to essentially "firewall" the Control Core's access the CSP network, not allowing it to send errant commands to critical CubeSat Bus subsystems.

It is also possible to use a Peripheral CSP network to pass CSP commands to the CubeSat from the ground through the S-Band radio link. By using HMAC to verify the origin of the packets, CSP commands can be sent via the S-Band radio, through the Control Core to the NanoMind where they can be authenticated and passed to the CubeSat Bus CSP network. This gives OPS-SAT a redundant ground link to the CubeSat Bus without risking the possibility of the Control Core issuing errant CSP commands to the CubeSat Bus.

1.1.9 Mechanical Configuration

The baseline mechanical configuration for OPS-SAT is shown in Figure 5. The panels used in the current mechanical layout are stand-in panels, as panel CAD was not supplied by Clyde Space. The baseline configuration has sufficient volume to accommodate the CubeSat bus, all payloads minus the NanoCam, and 3U deployable solar panels.

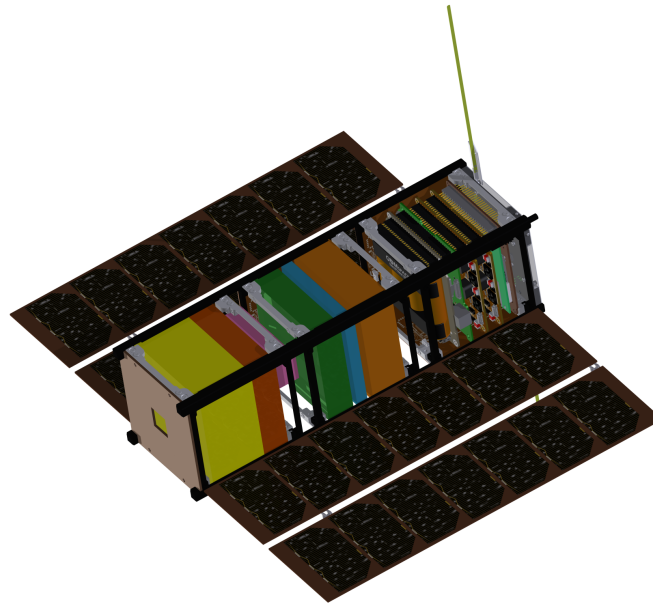


Figure 5: Preliminary baseline OPS-SAT mechanical configuration

The NanoCam is not in the baseline configuration because of the volume it takes up in the ISIS structure. First, the smallest NanoCam extends approximately 47mm inside the spacecraft from the end of the CubeSat structure. This uses a significant portion of the payload volume, forcing the removal of at least one other payload to accommodate the NanoCam. Figure 6 shows the volume the NanoCam uses, and how it would affect the placement of other payloads.

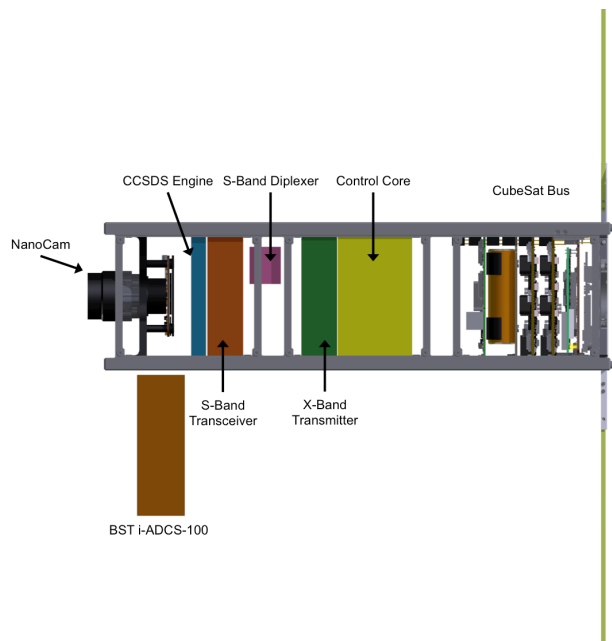


Figure 6: Payload volume restriction

As demonstrated by the figure the design still has risks concerning mechanical integration that must be addressed through: reduction in the number of payloads, redesign of the structure, and optimisation in the subsystem designs. This problem is currently left as a problem to solve early in the next phase.

2.4. Experimenter ICD

In order to understand the needs from the experimenter community for documentation and tools to support their development of the software experiments parallel to the OPSSAT satellite all proposal delivered by the community has been reviewed and additional direct feedback has been requested from the community.

This has resulted in a roadmap for artefacts that the OPSSAT project will need to deliver to the experimenter community in each phase of the mission, as well as an example API to demonstrated how capabilities provided by OPSSAT shall be made available to experimenters. This work is presented in the Experimenter ICD document.

2.5. Development Plans

Parallel to the completion of the study contract clarity on implementation of the next phase of the project was reached as national delegations committed budgets and the overall development plan got approved by the ESA Industrial Policy Committee. Within the study detailed development plans where delivered in line with the OPSSAT Program development plan with detailed focus on contributions required by consortia members in the next phase. The contributions are outlines below:

- GomSpace:
 - Development and delivery of redundant power supply system
 - Delivery of core Cubesatbus avionics stack
 - Procurement of solar panels
 - Development and delivery of safe mode ADCS software
 - Delivery of Cubesatbus CDH framework to GMV and support hereof for the mission
 - Delivery of tailored NanoCam payload
 - Support to systems engineering and Cubesatbus AIV

- GMV:
 - Development and delivery of ADCS flight software for Nominal mode operations
 - Development of ESOC compliant Command and Data Handling Software
 - Support to integration activities

3. Conclusions

In conclusion this Phase A-B1 study contract has provided:

- Confirmation that the mission concept described in phase 0 is feasible and relevant
- Consolidation of mission objectives and mission requirements
- An updated mission architecture and system design solving many of the problem areas identified in Phase 0
- A roadmap for distribution of relevant documentation and tools to experimenters throughout the project

Based on the current status of the design a number of risk areas have been identified which must be addressed in the final work leading to a PDR level review:

- Mechanical configuration needs to be readdressed to ensure that all payloads can be accommodated, or the number of payloads has to be reduced.
- It has been identified that the power budget is very sensitive to changes in LTAN of the orbit. As the orbit will be decided based on launch availability the design needs to accommodate all scenarios. This study suggests an operational concept for power cycling of the S-band equipment to ensure adequate power margin under worst-case conditions.

To meet the customer requirement of disruptive innovation in the field of software for spacecraft operations the OPSSAT design will deliver performance that significantly advances the state-of-the-art for nano-satellite missions. To do this the design relies on a number of new technologies and systems becoming available from the European Industry and with this perspective OPSSAT will also be of great value to the European nano-satellite industrial base.

The integration of these new systems and capabilities, however, put great responsibility on the prime for the next phase of the program implementation to appropriately manage risk and diligently track progress of all sub suppliers.

GomSpace, GMV and Villemos Solutions look forward to support the continuation of the OPSSAT programme.