MIST

Miniature Student Satellite

A project overview

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A WORD OF CAUTION

This document is based on a proposal document submitted in October 2019 to the European Space Agency's Fly Your Satellite competition for ESA support and launch of the satellite. KTH eventually withdrew for this competition because it did not fit our schedule or our resources. However the proposal is a good summary of the project. However, there have been substantial changes in some areas since October 2019, in particular the chapters on on-board software (section 2.2.4) and modes of operation (sections 1.5 and 1.6). Therefore these chapters will be rewritten soon. In other areas changes have been much less radical since October 2019.

ABSTRACT

The Miniature Student Satellite project, MIST, is a 3U Cubesat project carried out by the KTH Royal Institute of Technology in which students perform system level design, integration, test and operations. The nadir-pointing satellite carries five experiment from KTH and industry some of which aim at demonstrating new space science instruments (X-ray detectors) or electronics technologies (single event upset detection and SiC circuits). MSc students work for academic credits for up to two semesters or work on their theses in the project. The team leader is a senior manager from space industry. The sponsoring professor is former ESA astronaut Christer Fuglesang, now professor of spaceflight technology at KTH. The project started in 2015 and is approaching the final phases of system level functional and environmental testing.

ABBREVIATIONS AND ACRONYMS

Abbreviation	Description
ABF	Apply Before Flight connector
ADCS	Attitude Determination and Control System
AFSK	Audio Frequency-Shift Keying
AntS	The ISIS deployable antenna system.
BOL	Beginning of life
BPSK	Binary Phase-Shift Keying
COTS	Commercial Off-The-Shelf
CSKB	Cubesat Kit Bus
EOL	End of life
EPS	Electrical Power System
FDIR	Fault Detection Isolation and Recovery
HDRM	Hold Down and Release Mechanism for the solar panels
I^2C	Inter-Integrated Circuit, serial computer bus.
IARU	International Amateur Radio Union
ICD	Interface Control Document
iMTQ	ISIS Magnetorquer/magnetometer subsystem
ISIS	Innovative Solutions in Space B.V., the subsystem supplier for MIST.
KTH	Kungliga Tekniska Högskolan, i.e The Royal Institute of Technology
LNA	Low-Noise Amplifier

MCS	Mission Control System
MPPT	Maximum Power Point Tracker
OBC	On-Board Computer (sometimes referred to as iOBC=ISIS OBC)
SEAM	Small Explorer for Advanced Missions
SEUD	Single Event Upset Detector
SiC	Silicon Carbide (experiment)
SoC	State of Charge
SPS	Solar Panel Simulator
TBC	To be confirmed
TBD	To be determined
TRXVU	ISIS Transceiver, UHF Transmitter and VHF Receiver
UHF	Ultra-High Frequency
Vbat	Voltage at Battery
VHF	Very High Frequency

1 MISSION DESCRIPTION

1.1 Mission Context

The KTH Space Centre coordinates and promotes space-related activity at several KTH departments, with an overarching objective of establishing KTH as a "Space University" and a hub for Swedish space research and technology. One of the main activities of the Space Centre is to strengthen KTH’s participation in projects involving students.

The main such activity of the Space Centre is the MIniature Student saTellite (MIST) project was defined in 2014 at the initiative of the KTH Space Centre director professor and ESA astronaut Christer Fuglesang. In a memo dated 14 March 2014, associate professor Nickolay Ivchenko set out the basic ideas behind the student satellite project in this way:

“... KTH has expressed an ambition to start up a student nanosatellite program – based on CubeSat concept. Ideas for the mission objectives (beyond the pure educational one) will be solicited under spring 2014. This document briefly describes a concept suggestion.
The main idea is to have the satellite as a test/demonstration platform for new technical solutions, which would come both from industry and KTHs own research/development). The student team (under a supervision of interdisciplinary team of teachers at KTH) builds a satellite platform based primarily on the commercial off the shelf (COTS) subsystems, where the payload is provided by “external customer” (a company or a research group – at KTH or another university in Sweden). In the case of a company, certain sponsorship will be expected – at minimum contribution of the payload in kind, and support for the student payload teams, but ideally some funding towards the project. No cash flow is expected if the “customer” is an academic group.

Benefits for the students:

- Getting a system-level overview of a satellite
- Working with real industry as a customer, getting contacts
- Fast turnaround (COTS subsystems, “customer”-provided payload)

Benefits for the “customers”:

- Fast turnaround, in-orbit demonstration of hardware, without having to drive the whole project
- Non-committed access to students (the "customer" company gets to work with some students "taking care" of the company's payload quite closely without any obligation on the company's side)..."

It is financed by the center through KTH funds and external donations, and managed by an experienced manager. In MIST students can participate in the design, test, launch and operation of a real satellite and it enables KTH researchers and companies to test new technology ideas in space. These include demonstrating new X-ray detector technology in the CUBES experiment, testing new methods for detecting and correction Single Event Upsets, manufacturing SiC circuits and other exotic semiconductor components for use in space. These three experiments certainly require space-based experiments.

1.2 Mission Objectives

The main objectives of MIST are:

- Giving students hands on experience within a real space project where students learn about working methods and teamwork style in the space industry as well as being able to work on their BSc or MSc theses within the project.
- Forming close links with the local space industry for mutual benefit.
- Developing a body of experience within KTH in running space projects.
- Increasing the visibility of KTH among students, not only in Sweden.
- Giving KTH researchers the opportunity to develop new instrumentation or technology ideas for use in other projects.

Achieving the objectives above is the criterion for the basic success level in the project. The table below is a "success ladder" of the project.

Success level	Criterion
1	>120 students have worked on the project
2	The satellite passes all ground testing and is ready for launch.
3	Reliable two-way radio contact is established with the satellite.
4	The basic functions of the satellite work normally in orbit.
5	At least one of the KTH experiments on the satellite deliver useful data.
6	All KTH experiments on the satellite deliver useful data.
7	All experiments on the satellite deliver useful data.
8	The satellite provides some useful data during one year in orbit.

1.3 Mission Analysis

The intention is to put MIST into an approximately circular sun-synchronous orbit at 500 ≤ h≤ 660 km altitude with an LTDN/LTAN between 0900 and 1100. For all analysis in the project an SSO in this range has been selected: at h≈640 km and LTDN=1045 has been selected. The reasoning behind this choice is discussed below.

Many Cubesats are launched from the International Space Station, which is in an orbit at about 400 km altitude at an inclination of 51.6°. First of all, the maximum elevation as seen from Stockholm of a satellite in such an orbit is about 20° leading to rather limited total contact with the satellite. Secondly, the physical lifetime in an orbit at that altitude due to air drag is limited, i.e. 1-2 years (Figure 1). Thirdly, the attitude perturbations due to air drag are considerable in such an orbit making it hard to achieve the goal of pointing within ≈20° of nadir. Therefore ISS orbits are not suitable for MIST. Figure 1 has been computed using NASA's Debris Assessment Software, freely available on line.

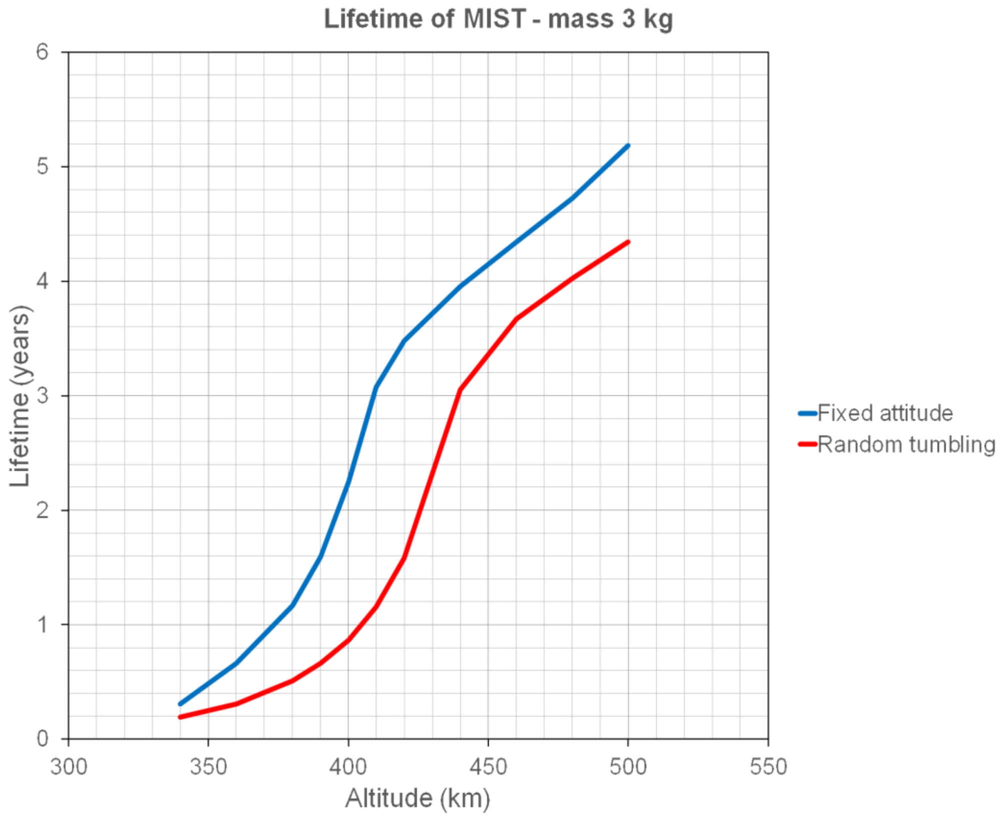

Figure 1 Lifetime of MIST in the altitude range 350-500 km.

The number of launches per year to sun-synchronous orbit is rather high and launches into such orbit with Earth observation satellites often carry many Cubesats as secondary passengers. Typical orbits achieved in such launches have been analyzed and a "reference orbit" has been developed. This notional orbit is designed such that it represents a probable case not far from what the final parameters may turn out to be.

The orbital elements for the reference orbit are defined for **0000:00 UT on 21 June 2017**. The orbit is defined so that the LTDN=1045. Furthermore, the sun-synchronous orbit is defined so that its ground track repeats every 4 days, or 59 revolutions around the earth. The TLE[1] for the reference orbit reads like this:

```
MIST Reference Orbit
1 99999U 17040A   17172.00000000  .00000000  00000-0  00000-0 0  0012
2 99999 097.9430 250.6332 0010000 000.0000 000.0000 14.75896000 00001
```

The interpretation of these numbers is:

```
Satellite:        MIST
Catalog number:   99999 (fictitious)
International nr: 17040A (fictitious)
Epoch time:       17172.000000000
Element set:      1
Inclination:      97.9430 degrees
RA[2] of node:    250.6332 degrees
Eccentricity:     0.0010000
Arg of perigee:   000.0000 degrees
Mean anomaly:     000.0000 degrees
Mean motion:      14.75896000 revolutions/day
Decay rate/2:     0.00000000 revolutions/day^2
Epoch rev:        0
```

The maximum altitude of the satellite is determined by the internationally recognized Space Debris Mitigation Standards which states that for non-maneuverable space objects an orbit has to be chosen where their post-mission lifetime does not exceed 25 years.

To determine this orbital altitude for MIST the NASA Debris Assessment Software 2.0 has been used. A satellite geometry as defined by Figure 6 was used.

DAS was run with sun-synchronous orbits at the same LTDN as the reference orbit, but with varying altitudes and corresponding inclinations. DAS can also estimate the area/mass ratio of the satellite in the direction of flight for different attitudes. The most realistic attitude to use for long-term simulations of the lifetime is “random tumbling”, assuming the satellite is no longer operational and attitude control is no longer active. To study the effect of varying mass of the satellite DAS was run for both 4kg (red curve in Figure 2) and 3 kg (blue curve in Figure 2). Random tumbling leads to the lowest lifetime. A line showing the maximum allowed orbit life time 25 years is also included.

The graph shows the obvious result that a light satellite has shorter lifetime. The reason for the “kinks” in the plot is the effect of the 11-year solar cycle affecting the lifetime of the satellite. It appears from that 660 km is a reasonable estimate of the maximum permissible altitude for MIST. Attitude control simulations indicate that the altitude should be kept

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[1] TLE=Two-Line Element set, used by space-track.org.

[2] RA=Right Ascension, ”sky longitude”.

above 500 km to avoid large excursions in nadir-pointing attitude due to air drag perturbations.

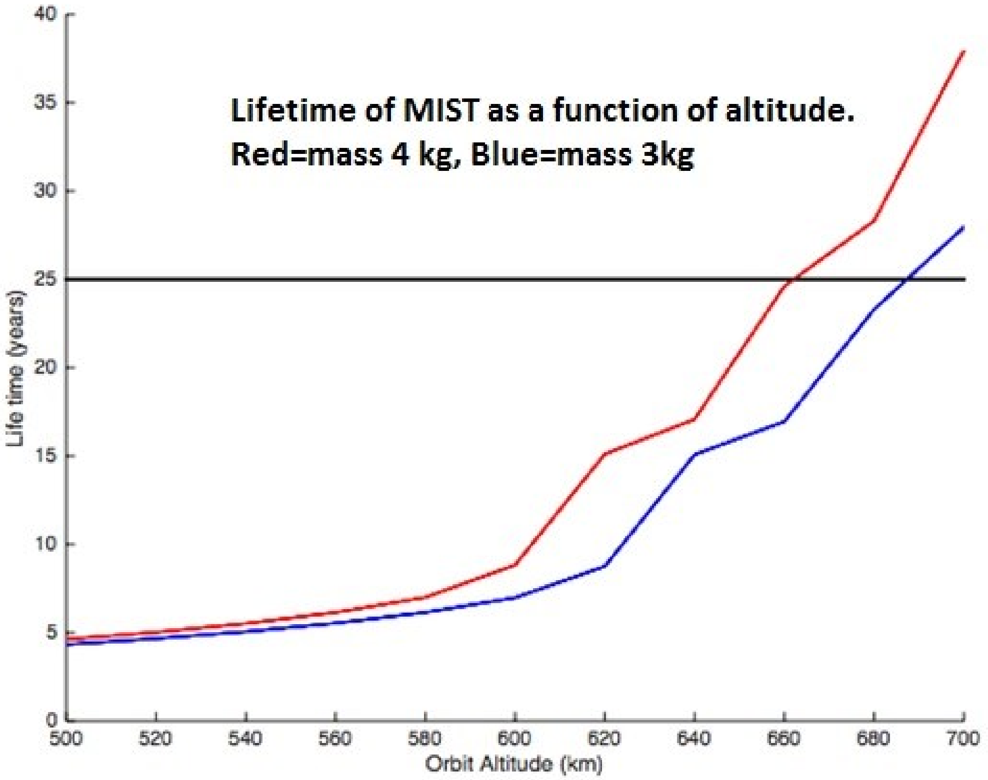

Figure 2 Lifetime estimate of MIST at different altitudes and masses.

1.4 Mission Phases and Mission Timeline

Figure 3 shows the easily identifiable mission events. Events 3 and 4 can actually be run in the opposite order since tip-off rates from the launch vehicle is probably well within the limits of the de-tumble capability of the magnetic control system. Between events 5 and 6 the commissioning of the satellite will take place. This will involve verifying that the attitude control software works properly followed by checking out all the basic functions of the on-board computer software as well as checking that on-board temperatures are within reasonable limits. The camera should be operated early in the mission to provide images that can be used for public outreach.

A one year operational period is foreseen. After that the satellite may be maintained in operation, but at a lower level of activity in which data from only some experiments are collected.

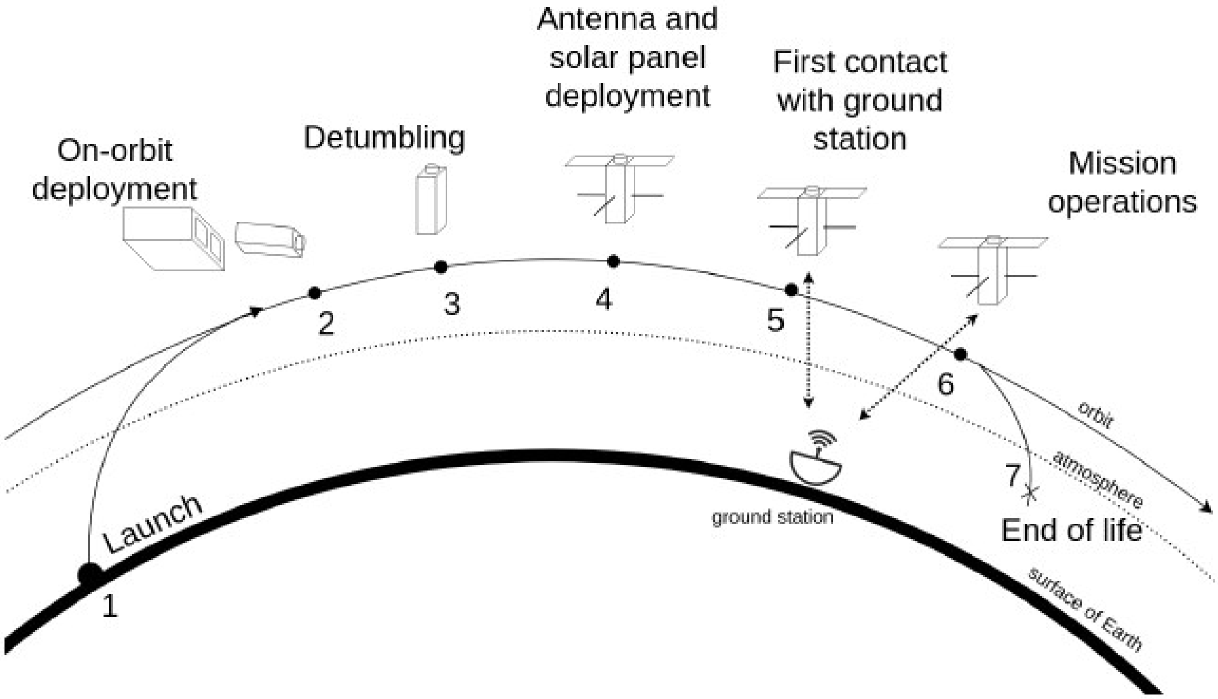

Figure 3 Mission phases.

1.5 CubeSat Operational modes

The following modes can be identified (see Table 4 on page 40)

- Initialization mode
- Commissioning mode
- Mission mode
    - Idle, non-oriented operation
    - Normal, oriented experiment operation
    - Nanoprop experiment operation
- Safe mode
- Troubleshooting mode

The ***initialization mode*** is an automatic sequence that is “timer- and logic-based”. The steps in this mode are:

1. The Kill-Switches are released when MIST is separated from the launch vehicle.
2. This turns on the Electrical Power System (EPS), which also turns on the Onboard Computer (OBC)
3. The OBC starts executing the initialization code, among which is a function to instruct the EPS to turn off switchable outputs and to start a 30-minute timer
4. The OBC waits for 30 minutes (a typical launch vehicle requirement)
5. The OBC sends signals via its Daughter Board to deploy the solar panels.

6. The OBC checks for indications of solar panel deployment. (If it can be reliably done, otherwise step 7 is just carried by timer action).
7. The OBC sends commands for antenna deployment if the solar panels are deployed.
8. The OBC checks for antenna deployment. (If it can be reliably done, otherwise step 9 is just carried by timer action)
9. The magnetorquer/magnetometer system (iMTQ) detumble function is activated by the OBC.
10. The transmitter is switched into beacon mode.
11. The OBC checks if detumbling is complete.
12. The OBC S/W goes into “commissioning mode”...

If step 10 should be part of the initialization mode can be discussed. It could be the first action in the “comissioning mode”. The deployment of solar panels and antennas can be done before the de-tumbling since the rates at separation very rarely exceed 5°/sec.

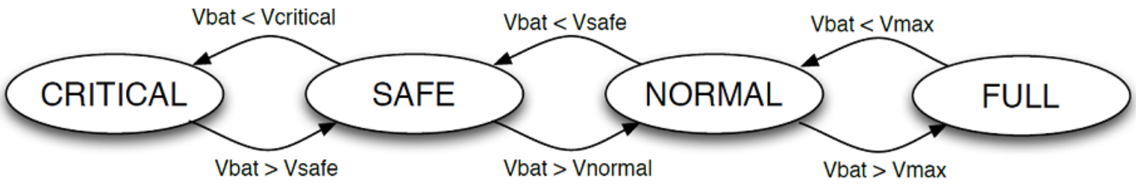

Figure 4 Software battery low-voltage protection.

The ***commissioning mode*** starts with the satellite in idle, non-oriented mode followed by subsystem evaluation and checkout followed by the activation of the attitude control system to enter into normal, oriented mode for experiment operations in which the satellite points within 20°-30° of nadir.

The ***mission mode*** is the oriented mode in which experiments can be run and includes the Nanoprop operation. Entry in oriented mode is commanded from the ground as is entry into de-tumble mode during recovery of normal attitude after a safe mode situation. Recovery from a situation where the battery low-voltage protection has been activated to the “critical” level means that the real-time clock needs to be reset and orbital elements may need to be uploaded to the satellite. All other mode transitions are automatic.

In the ***Nanoprop experiment operation*** the attitude control system could be run in two different configurations: the de-tumble mode to keep rates created by thrust misalignment in the four 1 mN thrusters of the Nanoprop system, or kept running to keep its Kalman filter running filtering magnetometer and sun sensor data.

Safe mode can have several reasons for being initiated. The OBC may be re-booted by the Electrical Power system watchdog timers or by FDIR functions watching over resource-hungry units such as Nanoprop. Loss of attitude and gradual discharge of the battery may also trigger battery low-voltage protection mode (Figure 4).

1.6 Concept of Operations

MIST operations are planned such that a single ground station should be able to handle all normal operations. On a typical day in orbit the total time per 24 hours above the horizon at KTH on passes longer than or equal to 3 minutes duration is 61 minutes spread out over 8 ground station passes. Five passes are longer than or equal to 8 minutes. The longest pass is 12 minutes. Figure 5 shows these passes and how they are distributed over the day.

Planning of operations is based around a weekly cycle of experiment operations. The CUBES experiment (see section 2.2.1), which generates the dominant amount of data, is run first in each such cycle and while other, less demanding experiments are run the following days while the CUBES data are downloaded. The Nanoprop (see section 2.2.1), propulsion system can be operated once a week, but in all probability Nanoprop will be operated less frequently.

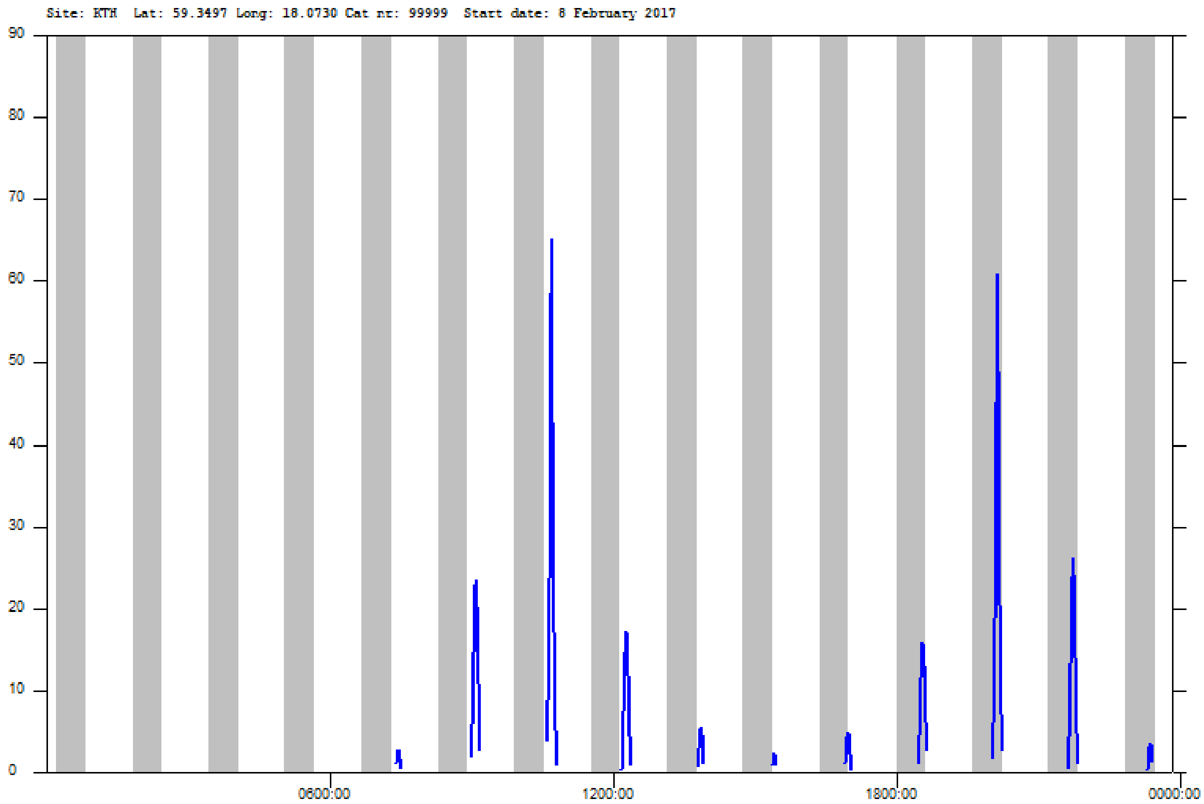

Figure 5 Elevation vs time for MIST as seen from KTH on a winter day. The grey areas are eclipse periods.

The short duration of passes makes it suitable to rely on time-tagged (here called “stored” commands) commands for performing routine operations like switching the transmitter on/off, collection experiment data, turning experiments on/off or other experiment operations.

New time-tagged commands are of course uplinked “manually” to the satellite. Standardized ground station pass schemes can be used to make the management of stored commands and the associated downlink of telemetry easier.

For simplicity’s sake the MIST on-board computer software is based on erasing stored experiment data as soon as it is transmitted to the ground (This does not apply to the camera image which has a special protocol handled directly by the camera itself).

Command purpose	Type	Reason/Notes
Transmitter ON/OFF	Stored	Housekeeping telemetry is turned on in real time when transmitter is turned ON.
Exp. Data download START	Direct	To avoid data loss if the ground station is off-line (due to some sort of failure) and the satellite transmits stored experiment data that are not received and also erased from on-board memory.
Exp. Data download STOP	Stored	To avoid data loss if a direct experiment data download STOP command is somehow missed (caused by, for example, bad satellite antenna pattern or the satellite slips below the horizon). The STOP command should perhaps be sent as a stored command together with START command.
Experiment ON/OFF	Stored	Mostly happens out of ground station range.
Exp. data storage ON/OFF	Stored	-"-
Exp. mode change	Stored	-"-

Time-tagged transmitter on/off commands stored in non-volatile memory to provde easy re-acqusition of the satellite in case the watchdog timers in the EPS have been triggered and tghe OBC has re-booted. In such brief power losses the real-time clock has not lost its setting.

Experiment data collection is done with one command specifying the interval between data polls, and the total # of polls, and the time when to start the polling sequence. You may call that a "macro command". This type of command is used when the experiment is turned on between data polls.

However, two experiments are turned on briefly and data is collected 15 and 24 times per day respetively. This creates a large number of stored commands. The table below shows an estimate of commands/day for each experiment.

Experiment	Total # of commands per day
M171 CUBES[3]	5
M172 LEGS	8×15=120
M174 NANOPROP	24
M176 SEUD	0

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[3] This is based on only running one CUBES at a time. This is still under discussion and may change to running two CUBES simultaneously.

Experiment	Total # of commands per day
M177 SIC	5×24=120
M178 Camera	5

The experiments are divided into different experiment groups. Each group runs for 24 hours, varying throughout a nominal week.

The total number of commands per day and experiment group is summarized in the following table:

Group number	Experiment in group	Total # of commands per group for 24 hours
1	SEUD, SiC	0+120=120
2	SEUD, SiC, CUBES	0+120+5=125
3	SEUD, SiC, LEGS	0+120+120=240
4	SEUD, SiC, LEGS, NANOPROP	0+120+120-8+24=256

These values are the sums of values for individual experiments, except for group number four. This is because the experiments LEGS and NANOPROP never run in the same orbit, so the values for one experiment run for LEGS (eight commands) is subtracted from the total. The experiments are foreseen to nominally run throughout a week according to the schedule below:

Day	Group	Experiments	Total # of commands per day
1	2	SEUD, SiC, CUBES	125
2	1	SEUD, SiC	120
3	1	SEUD, SiC	120
4	3	SEUD, SiC, LEGS	240
5	4	SEUD, SiC, LEGS, NANOPROP	256
6	4	SEUD, SiC, LEGS, NANOPROP	256
7	1	SEUD, SiC	120
Total # commands per nominal week:			**1237**

Table 1 Typical operational week for the MIST experiments and estimated number of commands.

The worst case is therefore seen to be days 4-6 with a total of 752 commands.

These are large amounts of commands. However, if the experiment that are turned on and off repeatedly could be handled in the same way as experiment data polls, many commads would be saved. Thus, a command type is needed with one command specifying the interval between on periods, the length of the on time, the # of on/off periods, and the time when to start the sequence. The plan is to implement this type of stored command.

2 DESIGN DEFINITION

2.1 System Description

2.1.1 *Physical Architecture*

MIST was defined as a 3U CubeSat in order to accommodate enough experiments to satisfy the project goals and its units are referred to as the top, the subsystem and the bottom stack. Experiments are located in the top and bottom stacks.
The subsystems for MIST were procured in open competition and the contractor for supplying the basic subsystems, ISIS[4], was selected in October 2015.

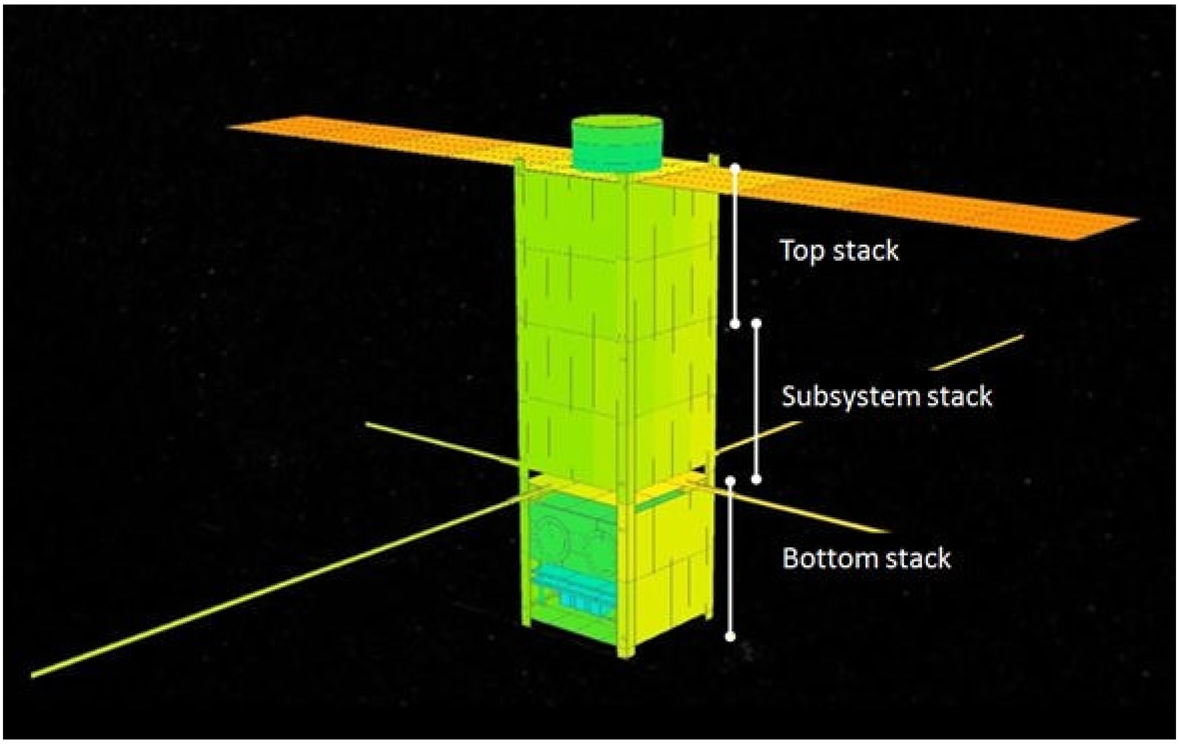

Figure 6 MIST overview. Down in the picture is toward nadir. The deployed solar panels are aligned with the orbital plane. (The image happens to be derived from thermal control simulations).

The MIST satellite is composed of its structure, its subsystems and its payload. In MIST the structure and the satellite subsystems, are mostly bought off-the-shelf from ISIS. The subsystems are:

- **An onboard computer**, abbreviated as OBC, "the brain" of the satellite..
- **A full duplex radio**.
- Two pairs of **deployable antennas**, one for transmit and one for receive.
- Deployable and body-mounted GaAs **solar panels**.
- Analog **sun sensors** to help determine the attitude of the satellite.
- A Li-ion **battery**.
- An **electrical power system** for battery charging and power distribution.

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[4] Innovative Solutions In Space, Delft, the Netherlands

- **Magnetorquers** with a 3-axis magnetometer to control and determine the attitude.
- IGIS, the **ISIS Generic Interface System**, for connecting experiments to the 104-pin connector stack connecting the main subsystems. Custom-made for MIST.
- HDRM, the **Hold Down and Release Mechanism** for the solar panels.

The reason that the hardware subsystems were procured from an outside source was that it would have taken a very long time to develop these subsystems "from the bottom up" using student manpower. The on-board software was the only major subsystem selected for development by students. Even so, ISIS supplied the so-called "Mission Support Package" and "Hardware Abstraction Level" software libraries to facilitate software development. Students have been deeply involved in specifying the mechanical and electric design of the IGIS and the so-called on-board computer daughterboard, which is described in 2.2.4.

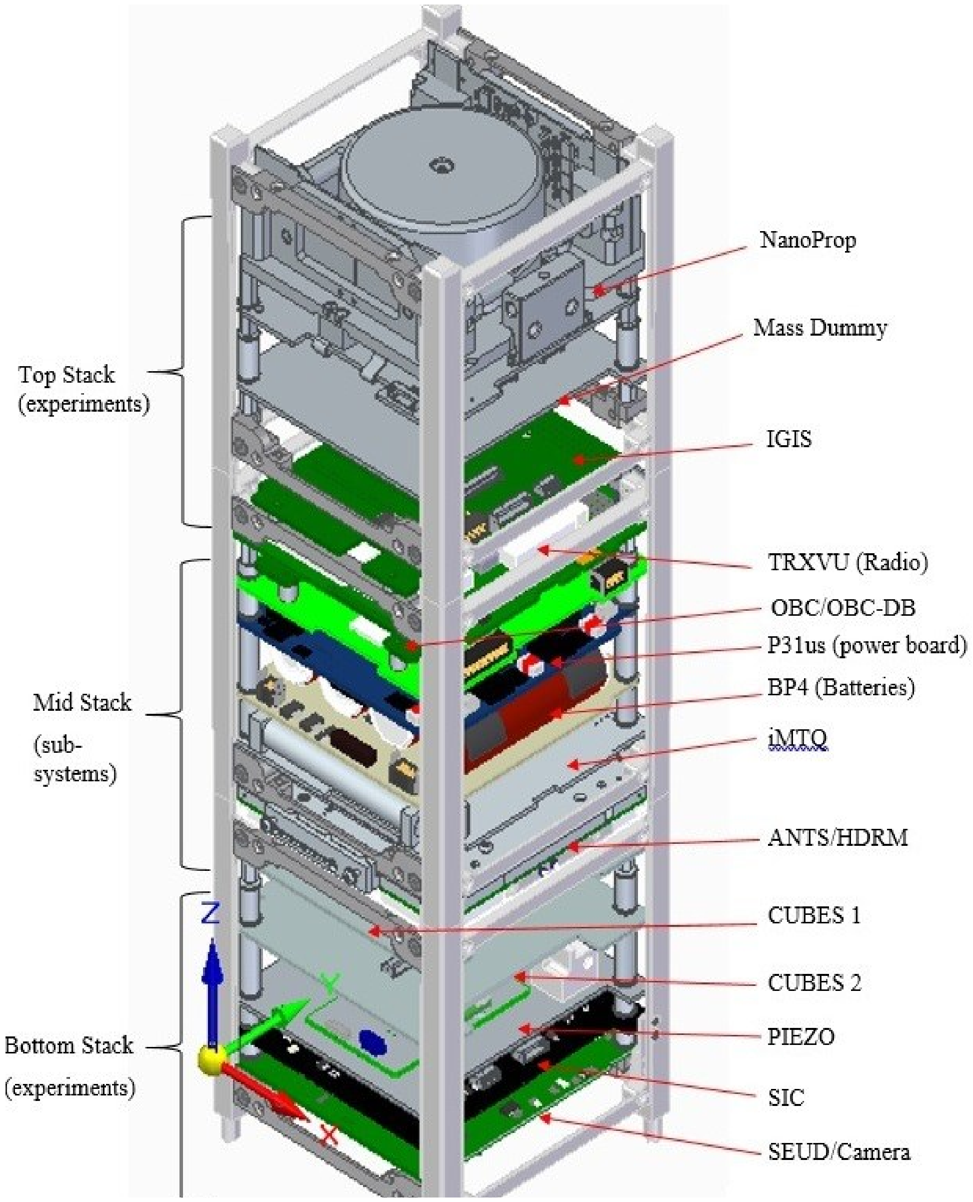

Figure 7 Accommodation of equipment after two experiments left the project.

Provide a block diagram of the physical architecture of the system showing the subsystems breakdown into hardware products or elements and their interconnection and interfaces.

Most of the subsystems described below are part of the so-called “subsystem stack”, the middle 1U part of MIST (see Figure 6 on page 15). Figure 8 below shows how the subsystems are mounted in this “stack”. The subsystems are connected via the 104-pin connector stack called the CSKB (CubeSat Kit Bus).

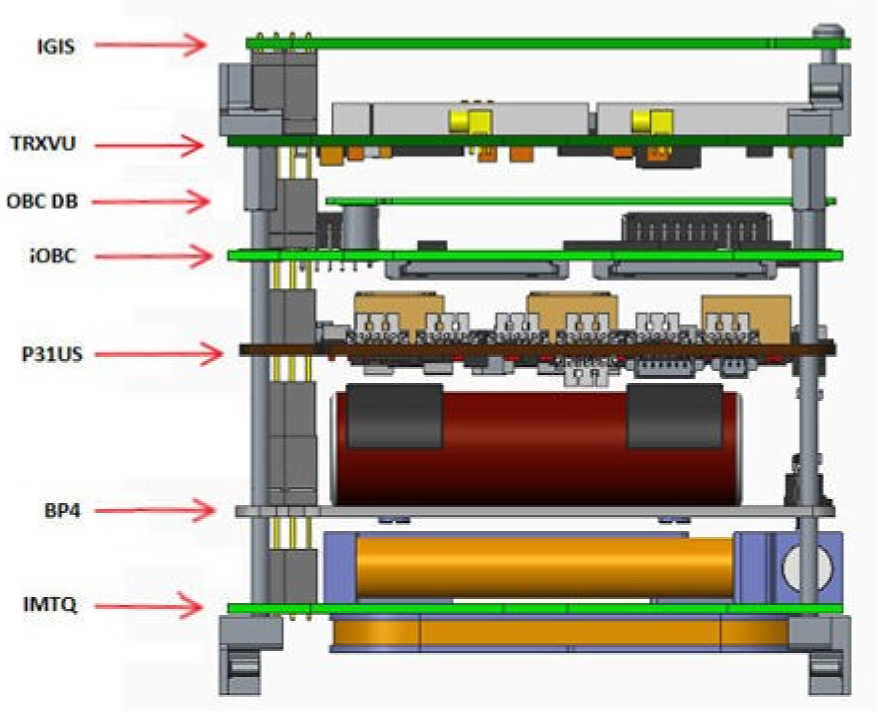

Figure 8 MIST "subsystem stack". From the bottom: iMTQ =Magnetic torque coils and magnetometer, BP4=Battery pack, P31us=Power supply, iOBC=Onboard computer, OBC DB=OBC Daughterboard, TRXVU=Transceiver, IGIS=ISIS Generic Interface System.

2.1.2 *Mass budget*

Table 2 represents the most recent knowledge about the mass situation. Experiment masses are still uncertain and so are the margins applied. However, the masses of the newly developed experiments represent a relatively small fraction of the total mass. Therefore the risk of exceeding the 4000 g mass limit is extremely small.

Unit	**Mass(g)**	**Margin (%)**	**Mass(g)**	**Rationale for margin**
Experiments				
CUBES_1	100	10	110	Prototype flown
CUBES_2	100	10	110	Prototype flown
Camera	47	5	49	COTS
LEGS	20	20	24	New board under design
SEUD	47	20	56	New board under design
SiC	31	10	34	Only small mods needed
Nanoprop (wet)	390	5	410	Flight model built
Experiments total	895		793	
Subsystems				
Antenna system	84	0	84	Weighed
TT&C	75	0	75	Weighed
Battery	240	0	240	Weighed
Electrical Power System	270	0	270	Weighed
Magnetorquer/magnetometer	196	0	196	Weighed
Onboard computer (OBC)	94	0	94	Weighed
OBC Daughterboard	27	0	27	Weighed
Interface board (IGIS)	38	0	38	Weighed
Hold-Down & Release Mech.	49	0	49	Weighed
Solar Panels	850	5	893	Mass from ICD of COTS
Structure and Cables	300	20	360	Harness is custom design
Subsystems total	2223		2326	
Total MIST satellite	3118		**3119**	

Table 2 MIST mass budget.

2.2 Payload & Subsystems Design Definition

2.2.1 *Payload(s)*

Name	**Purpose**	**Investigator, Organisation**
	TOP STACK	
M174 NANOPROP	Test of a Cubesat propulsion system	GOMspace AB, Uppsala
	BOTTOM STACK	
M171 CUBES	Study of X-ray environment in orbit	Mark Pearce Professor in Astroparticle Physics, KTH Physics Department
M172 LEGS	Test of piezoelectric linear motor	Piezomotor AB, Uppsala

Name	Purpose	Investigator, Organisation
M177 **SiC**	Test of silicon carbide electronics	Carl-Mikael Zetterling, Professor in integrated devices and circuits, KTH Electronics
M176 **SEUD**	New method for detecting Single Event Upsets (SEU)	KTH Electronics Associate professor Johnny Öberg
M178 **Camera**	Imager for public outreach etc.	SEUD + LiU, Visual Computing lab

CUBES

Satellites in low Earth orbit are subject to radiation in the form of charged cosmic rays, X-/gamma-rays and neutrons. The nature and intensity of the radiation varies with orbital altitude and position. For example, the Earth's magnetic field suppresses low energy particles at equatorial locations (so-called geomagnetic cut-off). In Polar Regions satellites pass through belts of trapped charged particles. Significant transient changes in the incident flux are also possible due to solar activity and (at X-/gamma-ray energies) thunderstorm activity in the Earth's atmosphere. The radiation environment encountered by satellites is complex and new mission proposals typically use computer models to assess potential measurement backgrounds to scientific instruments operated in space.

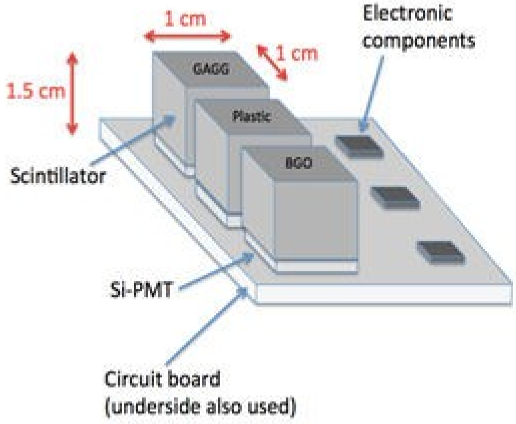

Figure 9 CUBES Overview.

The goal of CUBES is to study the in-orbit radiation environment using detectors comprising a silicon photomultiplier coupled to a scintillator material. The proposed components have been identified for use in future missions (e.g. the proposed SPHiNX mission for hard X-ray polarization studies of gamma-ray bursts). Deployment on a CubeSat mission will provide valuable qualification experience.

LEGS

PiezoMotor AB has delivered motors for various applications for a number of years. The motors are often used in rather harsh environments. These could include vacuum, high to extremely high magnetic fields, and radioactive surroundings. Occasionally space projects express interest in these motors. The purpose of flying a PiezoLEGS motor on MIST is to get more experience of using the motors in space applications, and also to get better data on how the motors really work in hard vacuum. Such data can also be of interest for extreme terrestrial applications.

Piezo LEGS motors are based upon piezoelectric elements that can stretch and bend in a certain way to create a walking principle, see figure. The motor technology is based upon direct drive with friction connection between the moving drive rod and the tip of the walking legs. This has a lot of advantages, but also makes the motor sensitive to wear. The wear increases with higher vacuum level and therefor the lifetime of the motor will be shorter in UHV for example than in normal lab environment. Piezomotor therefore seeks a better picture of the performance and how it changes over time during long time testing.

Figure 10 Piezo LEGS Linear 6N Special, LL10 Special, the motor selected for MIST.

SiC

Silicon carbide (SiC) has been proposed as a semiconductor material especially suited for harsh environments. Applications in space have been suggested, including even electronics for a Venus lander. The principal investigator's group has already demonstrated 500 °C operation of various integrated circuits (ICs), including operational amplifiers (OPAMPs). The functional tests have so far been performed using on-wafer measurements (unpackaged ICs) on Earth and in normal atmosphere. Already during the fall of 2014 a number of these ICs were packaged and bonded in standard through hole 14-pin ceramic dip packages (CERDIP) for reliability testing, including accelerated lifetime tests at elevated temperature, and in radiation environments. The transistors, being a general electronic building block, can very well be integrated in other electronics, mounted on one of the circuit boards. These SiC ICs will be flown on the MIST satellite, for in-orbit testing of low-TRL (Technology Readiness Level) technologies. These long term measurements will prove to be useful in the research of these electronics. The experiment consists of a SiC transistor, a Graphene transistor and a Silicon transistor.

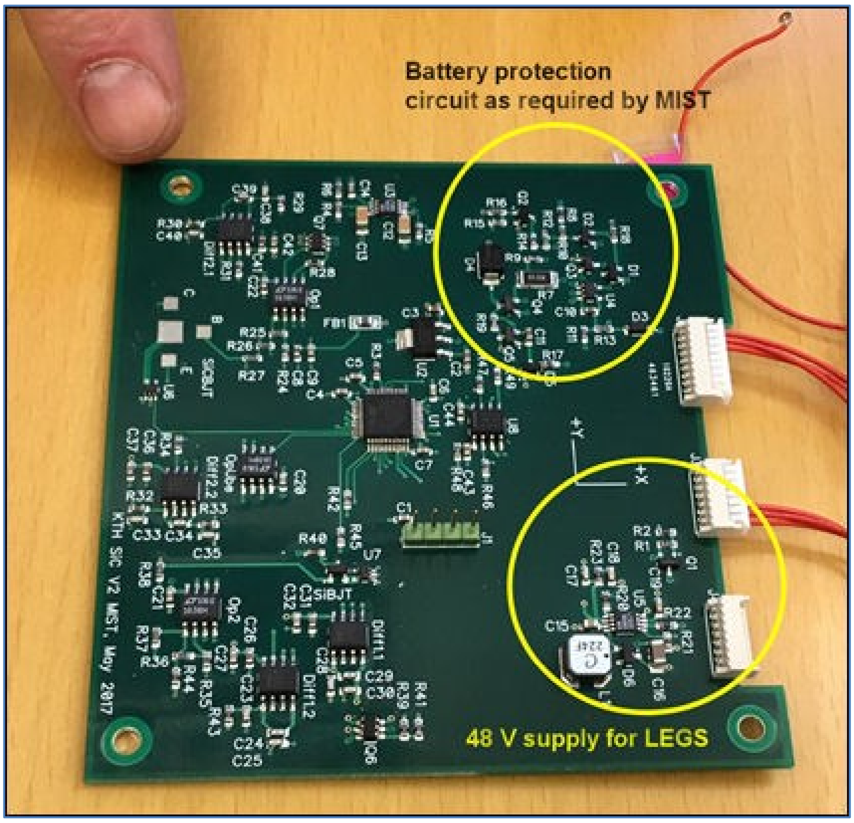

Figure 11 An early development model of the SiC experiment.

Nanoprop

As CubeSats attain more and more interest from industry and other players who want to use this platform for more advanced missions, propulsion capability becomes increasingly important. To date several hundred CubeSats have been launched, but only very few with any propulsion capability on-board. GOMspace is currently developing a propulsion module suitable for CubeSats, and getting flight heritage of this module is the overall goal for GOMspace with the subject experiment. In more detail, the goal would be to use the propulsion system in such a way that precision control of the satellite can be demonstrated (and thus proving the advanced closed loop thrust control functionality) and also to demonstrate the total impulse capability of the system that will be around 40 Ns.

The GOMpace propulsion subsystem for CubeSats (NanoProp) fits a half unit (0.5U) CubeSat. A schematic of the NanoProp subsystem is visible in Figure 12.

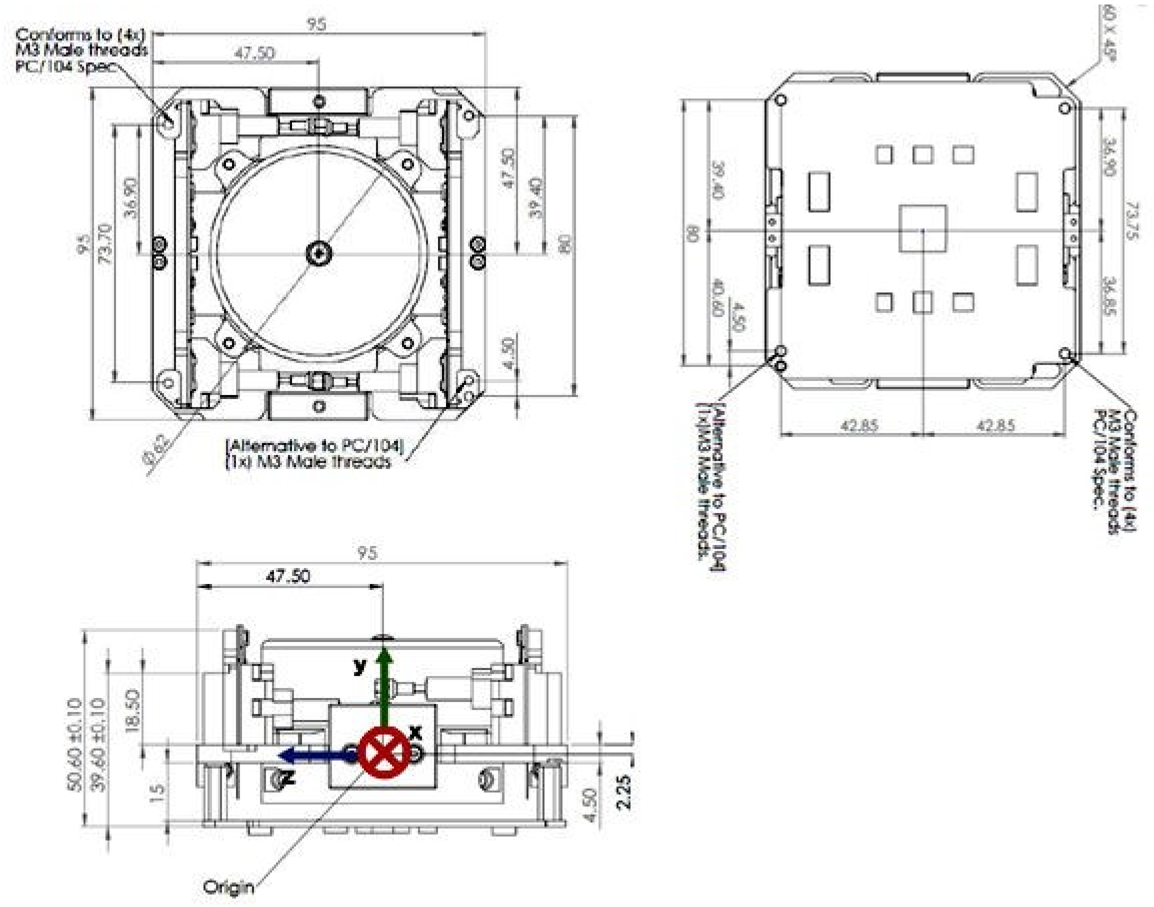

Figure 12 NanoProp dimensions

The system includes the following main parts:

- four MEMS thruster chips each giving 1 mN of thrust.

- a propellant tank for 50 g of n-butane giving a total impulse of 40 Ns,
- two isolation valves (one per tank outlet),
- four isolation valves (one per thruster)
- two filters,
- four interface electronics boards (one per thruster chip) and one main board,

These parts are mounted in a mechanical structure acting as support. The subsystem also consists of tubing to connect all gas components and their fittings. The NanoProp subsystem can be integrated in the standard ISIS Cubesat structure used by MIST. For easier thermal control of NanoProp it will probably be operated in sunlight.

SEUD – Single-Event Upset Detection

The purpose of this experiment is two-fold:

1. To test the KTH Electronics in-house concept for self-healing/fault-tolerant computer system in a hostile environment (like space) to see if it will be able to heal itself by correcting faults during run-time.
2. To measure the expected SEU frequency in near-earth orbit. The SEU detector can also be used to detect solar flares, since the number of SEUs/day is increased significantly when that happens.

Some Xilinx FPGAs have the capability to detect and correct faults caused by Single-Event Upsets (SEUs) in the configuration memory by reloading parts of the FPGA during run-time. Therefore, this technique can be used to build a Single-Event Upset Detector (SEUD) that measures/counts Single- Event Upsets that happens inside the FPGA. The minimum detection resolution time is dependent on the maximal scanning frequency of the selected device (~3-10 ms/complete chip scan). The FPGA itself can be configured with the necessary functionality and computers needed for controlling and surveillance of the SEUD.

The SEUD experiment will be used to support an OV5640 (color) image sensor normally used in mobile phones and digital cameras. SEUD will store and process the image in its considerable processing ability. The sensor is a low voltage, high-performance, 1/4-inch 5 megapixel CMOS image sensor with 2592 x 1944 pixels and 10-bit resolution. The pixel size is 1.4 µm x 1.4 µm pixel. The camera lens will have approximately 45° field of view so the ground sampled distance (GSD) is about 250 meters over an area of up to 700 km width. If an exposure time of 0.01 sec is used the satellite moves about 7.5 meters in this time, which is much less than the GSD. Attitude motion of the satellite contributes just a few meters to the blurring of the image. The camera will be located at the Earth-facing side of the bottom stack of the satellite.

2.2.2 *Attitude Determination & Control Subsystem (ADCS)*

Several experiments require at least a coarse steady pointing in the orbital frame[5]. An earth-pointing attitude within about 20° of nadir was selected early. By comparing with similar Cubesats it appeared feasible to achieve this with a magnetic attitude control

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[5] A coordinate system fixed at the satellite position in orbit, u=parallel to the radius vector, v=perpendicular to u and pointing in the direction of flight in the orbital plane, w=completing the right-hand Cartesian system.

system using analogue sun sensors and a magnetometer as attitude sensors and electromagnets as actuators. The electromagnets interact with the Earth's magnetic field to generate control torques. Analyses in the project confirmed this assumption.

M.Sc. theses conducted within MIST have shown that it will be possible to come close to the design goals for attitude determination accuracy and pointing error during sunlight, 5° and 15°. Simulations show that a control loop update frequency of 1 Hz works well. Even at 0.5 Hz update rate the pointing error is still less than 30°.

To develop the flight software for ADCS was regarded as too big a task to assign to students. Therefore it was decided to procure the ADCS software library from ISIS. Their software has flown on satellites configured as MIST.

The ISIS ADCS software allows to choose between an Extended Kalman Filter (EKF) and an Unscented Kalman Filter (UKF). It estimates a 7-component state vector made of quaternion and angular rates, plus the magnetometer bias. To calculate the initial state estimate it uses the TRIAD or QUEST algorithms. The ISIS ADCS library uses two different algorithms for control, depending on the ADCS mode. For de-tumbling, it uses the B-dot algorithm, while for normal operation it uses a PD regulator.

MIST is equipped with two sets of sensors to help determine the attitude of the satellite:

- **Analog sun sensors based on the** SLCD-61N8 solderable planar photodiode. The sensor has an angular response that roughly approximates a cosine shape over at least ±60° from the normal to the diode surface. Six sun sensors provide the direction to the sun during the sunlit portions of the orbit. Software in the OBC handles situations when the albedo radiation from cloud tops adversely affect sun vector determination.
- **A three-axis magnetometer** as part of the iMTQ unit (which also contains the magnetic torque) that uses the XEN1210 Hall effect magnetometer module with a resolution of 15nTand a magnetic field range of 63mT.

The attitude control actuator is a set of three magnetic coils, magnetorquers that are part of the iMTQ and commanded from the attitude control software running in the OBC. Two of the torquers are rods and one is a flat air coil. The magnetorquers are pulse-width modulated and have a maximum magnetic dipole moment of 230 mAm^2. The iMTQ is supplied by ISIS and is mounted as part of the CSKB connector pile in the subsystem stack.

The iMTQ has an autonomous function which can operate independently of the OBC called the de-tumble mode. This mode is used to reduce angular rates following separation from the launch vehicle and is active before the onboard software enters what can be called an operational mode in which the dedicated ADCS software in the OBC is active.

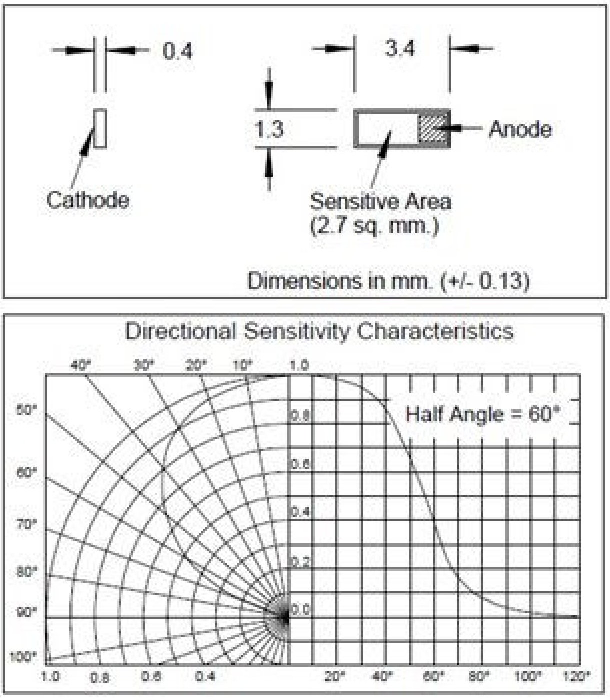

Figure 13 Analog sun sensor details.

2.2.3 *Electrical Power Subsystem (EPS)*

The power subsystem consist of the following min parts:

- The GOMspace P31us Power supply
- The GOMspace BP4 Li-Ion 39 Wh battery pack .
- The ISIS solar panels using GaAs solar cells from Azurspace

The P31us power supply:

- Interfaces to triple junction photo-voltaic cells and uses a highly efficient boost-converter to condition their output power in order to charge the provided lithium-ion batteries.
- Uses the incoming power along with the energy stored in the batteries to feed two buck-converters supplying a 3.3V@5A and a 5V@4A (configurable) output bus.
- Provides power to experiments via six individually controllable output switches with over-current shut-down and latch-up protection, each separately configurable to either 3.3 or 5.0 V.
- Supplies some experiments and subsystem with the battery voltage, which for MIST is <16.8 V.
- Has a microcontroller that provides maximum power-point tracking (MPPT) capability, measures and logs voltages, currents and temperatures of the system, enables user control etc. Using an I2C interface, it is possible to read out

measurements, control the on/off-state of 3.3V and 5V busses, switch on/off the MPPT and to set/read various parameters.
- Is equipped with watchdog timers to provide a degree of Fault Detection Isolation and Recovery. **The I2C watchdog timer** is triggered if the P31us has received no meaningful I2C communication for a period of time (length of period configurable by customer) it will switch off all outputs and do a reset, which will return the system to its original state. This can be used to solve a potential software fault in the on-board computer or similar. The **dedicated watchdog timer** is reset by a dedicated command to the P31us. This can for example be used as a ground communication watch dog, i.e. this command is issued to P31us on each connection with the ground station. If no communication has been received for a long period of time (configurable by customer), the P31us will switch off all outputs and do a reset.

The BP4 battery consists of four 2.6 Ah Li-ion cells connected in series and providing a maximum of 16.8 V. It has a nominal capacity of 38.5 Wh. It is protected against too low and too high voltage. The low voltage protection is implemented in both hardware and software.

- The hardware high voltage protection will set the input voltage on the solar cells to zero.
- The software high voltage protection implements a constant voltage charge scheme that will keep the battery at its maximum voltage while at the same time supping the users with the necessary power.
- The hardware low voltage protection will switch off the kill-switch, thereby disabling all outputs from the P31us and most electronics on the P31us itself leaving only the ability to charge the battery from the solar cells.
- The software low voltage protection is a three state system with a CRITICAL, a SAFE and a NORMAL mode.

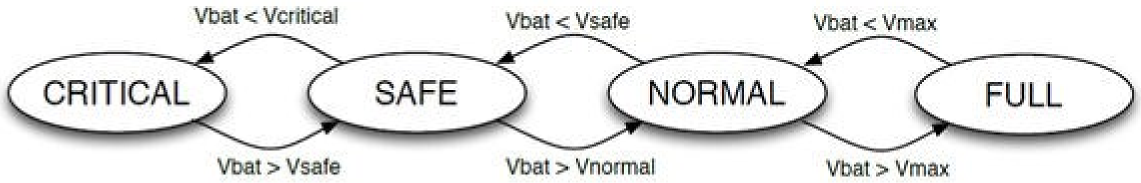

Figure 14 Software battery low-voltage protection.

In normal mode everything is nominal but should the battery voltage drop below V_{safe}, the P31us will change its output switch configuration to a safe mode configuration (user configurable). This allows the switch off of all non-essential systems and leave a simple low power beacon or similar running. Should the battery voltage continue to drop below $V_{critical}$, the P31us will switch off all user outputs. Note that "always-on" outputs will only be affected by the hardware protection.

BP-4 as configured for MIST has battery heaters which can be controlled from the P31usr. The heaters can either be controlled directly from the output side by switch on or off the heater through commands, or by an autonomous heater controller with the heater on and off temperatures settable through the configuration system.

The solar panels

The multitude of experiments requires deployable solar panels to meet the power demands. Initially four deployable panels were considered, but one face of the satellite must be able to have a 2π steradians view of the sky from the -X face of the satellite (see Figure 15). The X-ray experiment CUBES has its sensors located on the -X face. This required that no protruding solar panels could be viewed from CUBES leading to only two deployable solar panels (deployed from the ±Y faces) as can be seen below. It should be noted that the orbital frame shown in this figure relates to the nominal attitude of the satellite[6].

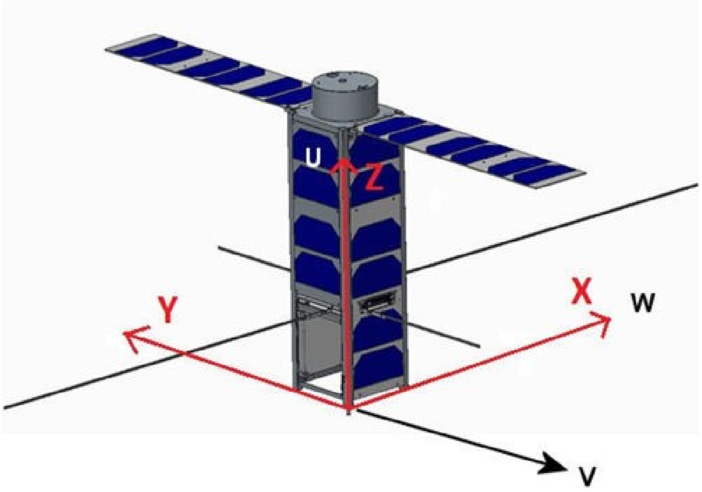

Figure 15 Solar panel configuration and the orbital and body coordinate systems in the nominal attitude.

Cells on opposite faces of the satellite should be connected to the same voltage converter (marked MPPT=Maximum Power Point Tracker in Figure 16) because opposite faces are never illuminated at the same time. The ±Y faces of the satellite are the same, while the ±X faces are different because of the requirement to have the bottom stack –X face without solar cells in order not to obscure the view of the CUBES experiment.

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[6] A coordinate system fixed at the satellite position in orbit, u=parallel to the radius vector, v=perpendicular to u and pointing in the direction of flight in the orbital plane, w=completing the right-hand Cartesian system.

The 3G30C cell type is an InGaP/GaAs/Ge on Ge substrate triple junction solar cell (efficiency class 30% advanced). The cell has an improved grid-design and is equipped with an integrated bypass diode, which protects the adjacent cell in the string.

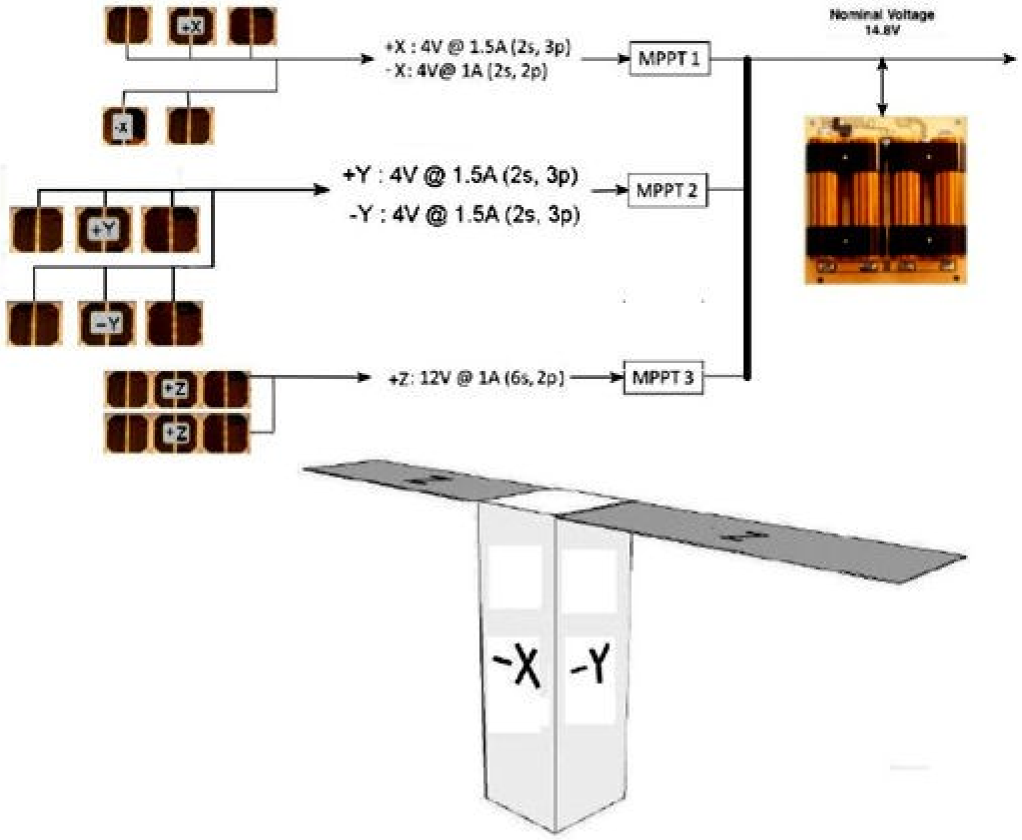

Figure 16 Cell layout on the MIST solar panels.

For estimating the available power on the satellite a comprehensive simulation tool has been developed by a student. It takes into account the satellite attitude (a few salient cases), the orbital motion of the satellite, the season, shadowing of the body solar panels by the deployed panels, scattered light from cloud-tops (albedo). To form a basis for simulations of the state of charge of the battery two simulations of available solar array power have been made for a nominal attitude and fully deployed solar panels are assumed:

- The worst case (2017-07-03, earth aphelion, Solar constant ≈1322 W/m^2) and
- Best case (2018-01-03, earth perihelion, Solar constant ≈1414 W/m^2)

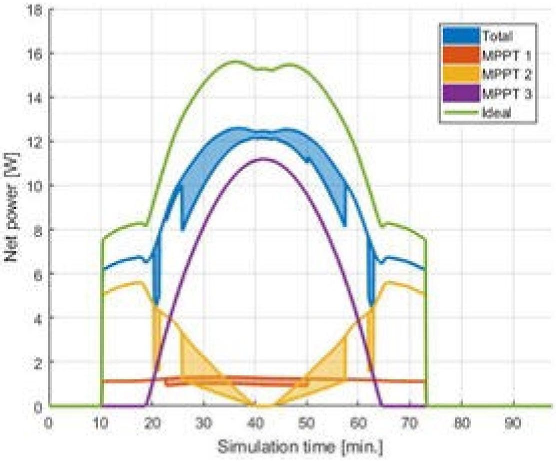

Figure 17 Worst case solar panel output.

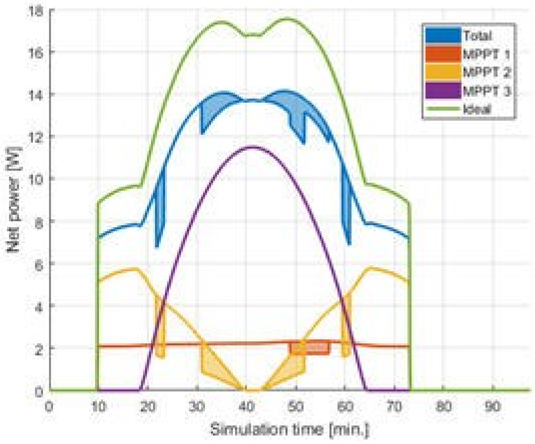

Figure 18 Best case solar panel output.

Figure 17 and Figure 18 show these two simulations of the power output as a function of time during one full orbit. The variations shown as solid areas are due to fluctuations in choosing the maximum power point by the MPPTs. The green line represents the ideal power (the power if each cell is individually controlled at its maximum power condition and no losses) and is shown for comparison with other methods. The total power generated per orbit in the two cases is as follows:

- Worst: Min 9.42 Wh, max 10.1 Wh, ideal 12.6 Wh.
- Best: Min 11.3 Wh, max 11.7 Wh, ideal 14.5 Wh.

The curves marked MPPT1 relates to power generated from the +X side panels and MPPT2 curve relates to the ±Y panels (along the track or opposite the track). MPPT3 represents the power from the deployed panels on the +Z side of the satellite.

This meagre power is what the satellite must operate on. A dynamic power budget model has been developed by students to compute the state-of-charge of the battery for various mikssion modes and experiment operation profiles. In this model the battery charge/discharge efficiency used is 85%, the EPS input regulator loss is 5%, and the EPS buck regulator losses are set at 10%.

The operation of the experiment will take place in so-called “power groups”. At the moment, the experiment with the highest estimated power consumption is CUBES experiment which now will run in two copies. Figure 19 shows that the state-of-charge of the battery never returns to 100% during a day when CUBES is operated. The CUBES units can therefore only be operated continuously during a single day and in the graph the state-of-charge drops below 80%, the limit recommended by the manufacturer. The CUBES experiment aims at gathering data over the entire planet. This can actually be done in 12 hours. If operated this way the state-of-charge is kept above 80%.

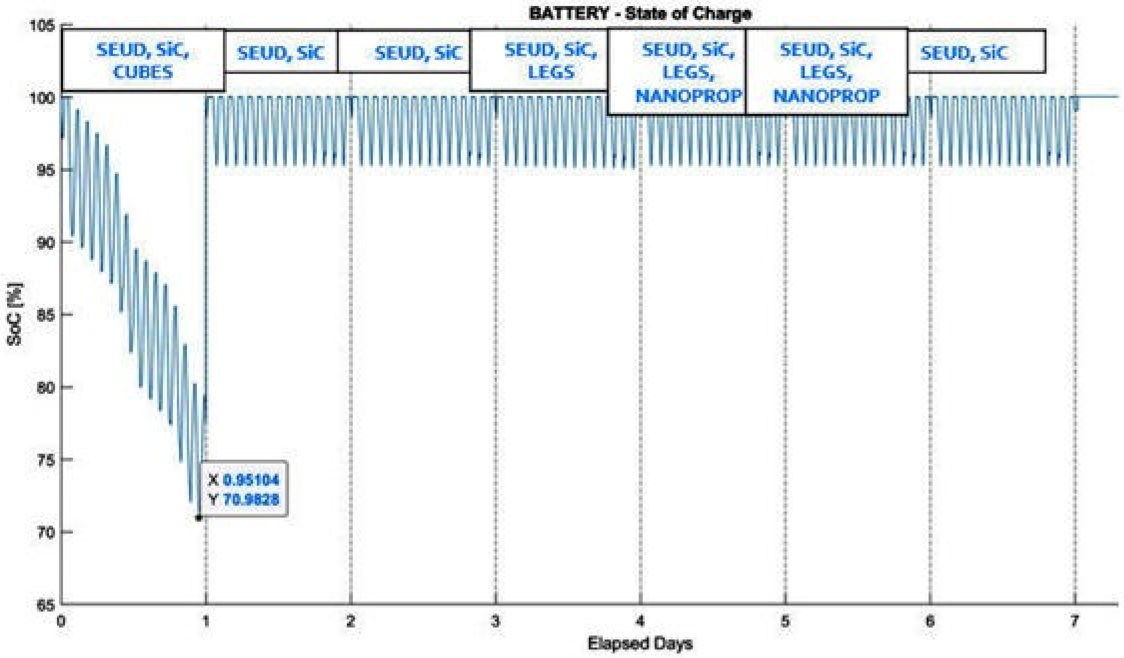

Figure 19 State-of-charge during a typical operational week.

Power and signal distribution

Connecting various parts of the satellite requires some unusual methods compared to conventional satellites. The subsystems are connected by the CSKB (The CubeSat Kit Bus) a 104-pin connector pile, but that pile only extends through the “subsystem stack”. To connect the rest of the satellite a cable harness is needed. That harness connects to the CSKB via the so-called IGIS (ISIS Generic Interface System), a breakout board.

To reduce the number of wires going from the IGIS out to the experiments a “daisy-chaining” concept is used. This means that power and data signals are not run in a “star” configuration, but that each experiment follows the preceding on the power and signal lines. This is shown in Figure 20.

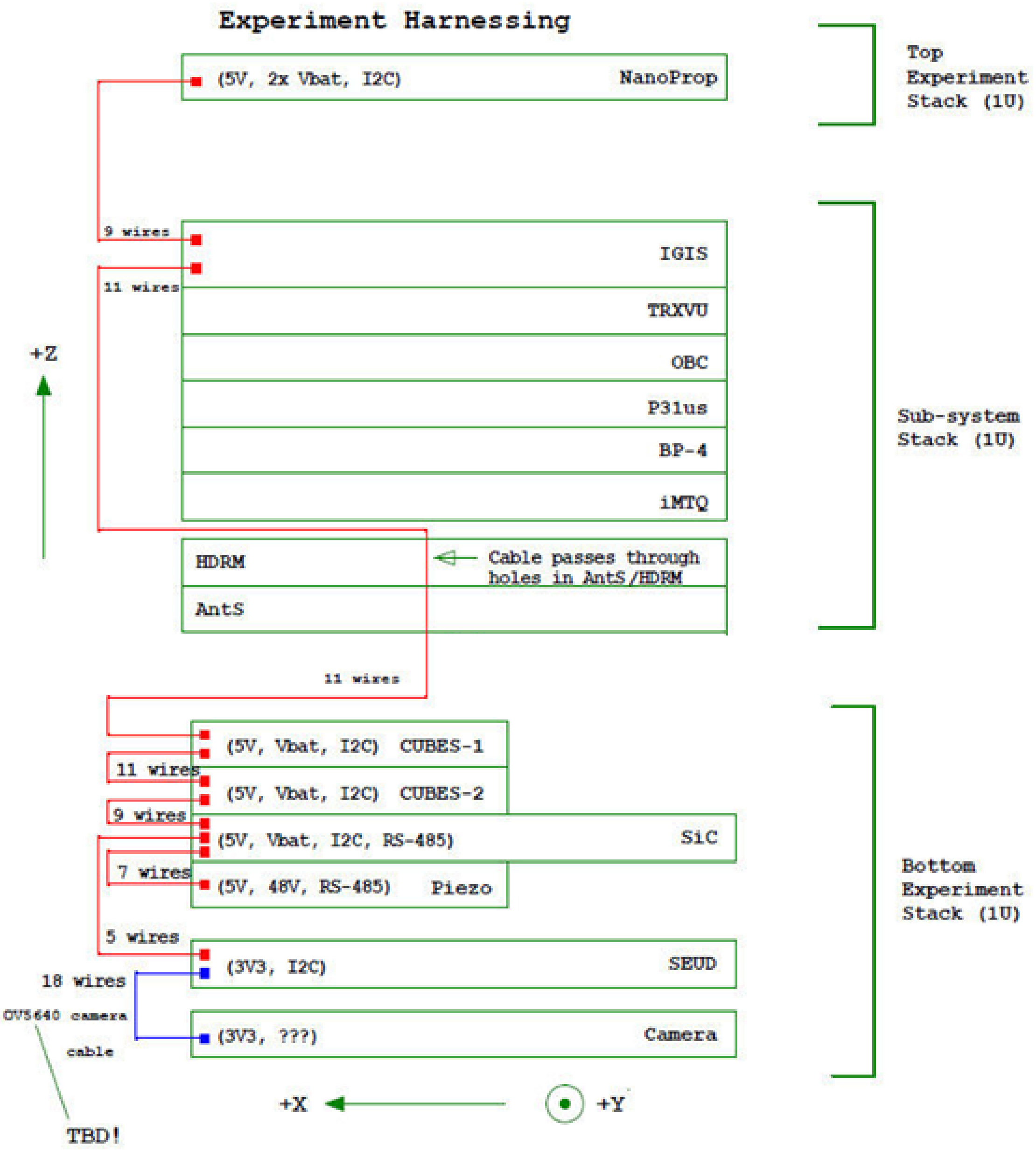

Figure 20 Experiment harness connections

2.2.4 *On-board Data Handling (OBDH) and On-board Software architecture (OBSW)*

Hardware

The on-board computer (see block diagram in Figure 21) used is ISIS iOBC. Its **main CPU** is a 32-bit ARM9 microprocessor from Atmel (AT91SAM9G20). Although quite powerful at 400MHz core speed, the processor is quite low-power as it uses 1.0V as its core voltage. The CPU has a number of interfaces to the outside world.

The **iOBC supervisor** is a PIC microcontroller that controls the power distribution across the board. It can individually switch on/off the CPU along with the other components of the board but separately controls the power of the RTC in order to keep the time on the satellite while the rest of the OBC is power-cycled. The power conditioning circuit includes overcurrent protection.

The supervisor also serves the crucial role of an **external watchdog** for the CPU. This is a window (frequency) based watchdog: If the CPU toggles the Watchdog-Reset line too frequently or not frequently enough, both cases will lead to the Supervisor power-cycling the OBC.

The iOBC contains two **Real Time Clocks**. The external RTC is an advanced Real Time Clock that is accurate as it compensates for clock-drift due to temperature variations. In addition, the CPU contains its own Real Time Timer as well.

The iOBC is equipped with the following **memory devices**:

- The CPU **executes its code** from this 32MB, low-power SDRAM. Volatile data is also stored here.
- The 1MB parallel NOR Flash is used for **storing code**. When the OBC boots up, the code is copied to the RAM for faster execution.
- The OBC has a 256kB FRAM which is a Non-Volatile storage medium that is more robust than Flash or EEPROM memories. The memory cells are not susceptible to Single Event Upsets (SEU) due to radiation. It will be used for storing **critical and changing data** such as flight parameters.
- The iOBC can use 2x 2GB SD-Cards for **mass non-volatile storage of data**. ISIS uses high quality industrial SD-Cards with Single Level Cell (SLC) Flash memory to improve reliability of the SD-Cards. Nevertheless, there are 2 cards for redundancy.

The OBC is equipped with a daughterboard to perform the following functions:

- Control the solar panels hold-down and release mechanism (HDRM)
- Retrieve HDRM deployment switch position data
- Retrieve solar panel sun sensor data
- Retrieve solar panel temperature sensor data
- To provide a two-wire interface to ABF (Apply Before Flight) signal from IGIS which is used to arm the iOBC (during flight preparation).

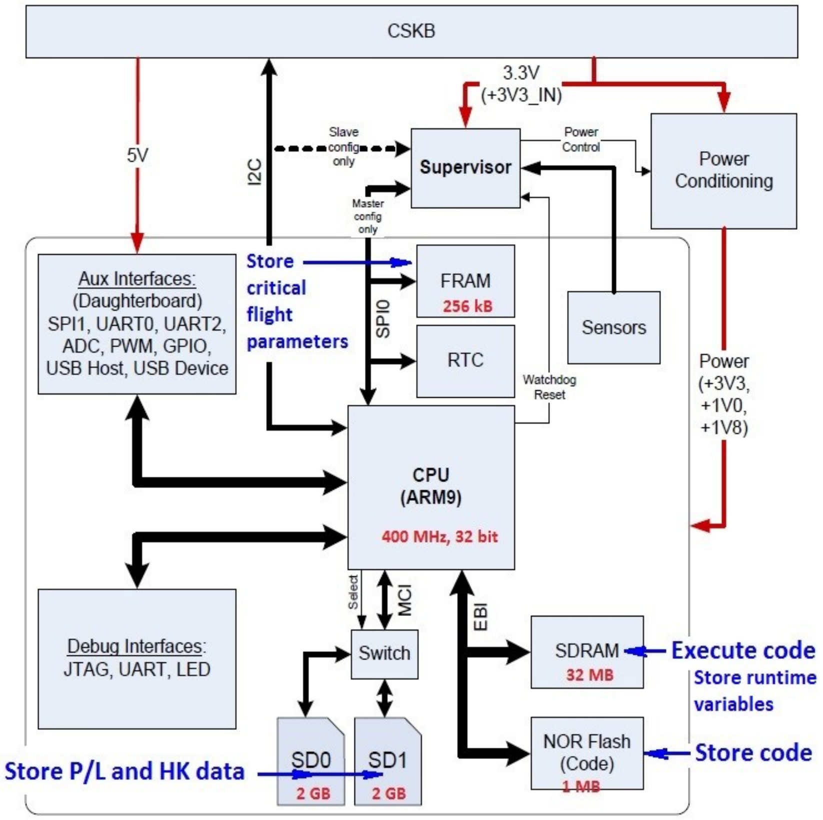

Figure 21 Block diagram of the OBC. HK=Housekeeping. P/L=Payload

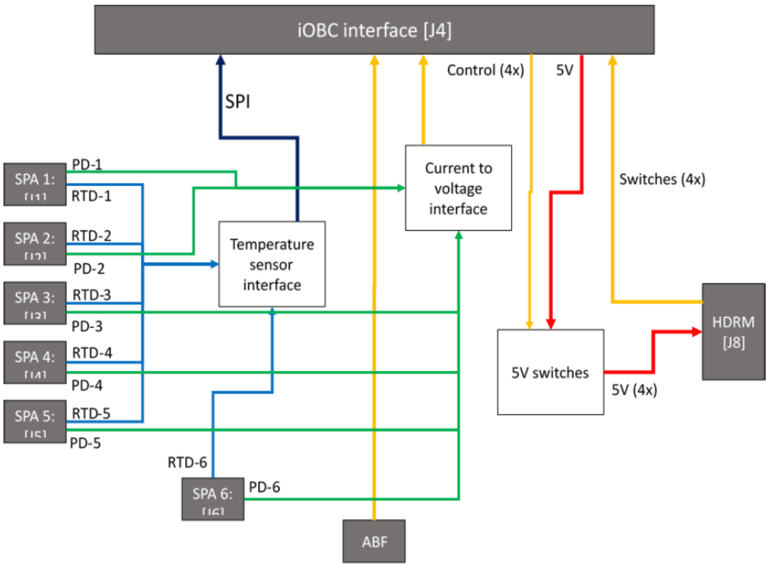

Figure 22 iOBC daughterboard connections.

Software

The **On-board software** is developed by students and supplies **critical spacecraft functionality** such as:

- Collects and stores data (telemetry) from experiments and subsystems.
- Transmits telemetry (stored and real time) to the ground (via the radio).
- Receives and executes commands (promptly or later) to experiments & sub-systems.
- An on-board time service for time-tagging telemetry and support attitude control.
- Determines and controls the attitude of the satellite (S/W supplied by ISIS).

ISIS software libraries “Satellite Subsystems Library”, “Mission Support Package” and “Hardware Abstraction Layer (HAL)” facilitate S/W development. The OBC runs the FreeRTOS operating system.

API’s

OBS (On-board Storage)

The OBS provides a simple to use API to read to and write from the FRAM and SD storage which includes data verification to make sure that no data is lost. It also provides specific functions to read from and write to queues such as the stored telemetry and telecommand queues. It’s also used in the implementation of the parameter database to store important information.

TMTC

The main purpose of the TMTC API is to encode outgoing telemetry and decode incoming telecommands. Messages sent and received by the TRXVU radio are formatted according to the AX25 protocol which contains messages in CCSDS PUS format. This needs to be unpacked or packed into internal structures within the OBC. Decode will rearrange incoming packets into telecommand structures while encode will arrange telemetry structured messages into outgoing packets which can then be interpreted by the ground station.

MSP

MSP stands for MIST Space Protocol which has been developed based on the principles of ABP (Alternating Bit Protocol) and is built on top of the I^2C protocol. It is used to communicate between the experiment tasks and the experiments. MSP communications are referred to as transactions, which consist of multiple frames sent back and forth between the communicating units. Both frames and transactions can be acknowledged. The frames sent are protected with a CRC. If a frame’s CRC is erroneous, the previous frame in the transaction will be acknowledged, signaling that the frame should be retransmitted. The MSP protocol keeps sequence flags to indicate the type of transmission as they have different requirements. As an example sending data and a data request will have slightly different transmission sequences. The sequence flags will be recovered if the OBC is reset as they are stored in the parameter database in FRAM, meaning that the OBC will not lose any data of the current transmission.

Mission Information Base

The Mission Information Base (MIB) contains various definitions, such as service types (ST), service subtypes (SST), and application process identifiers (APID). ST and SST are fields that are used in telemetry and telecommands to uniquely identify what they contain and thus handle them accordingly. They also have an APID field used to determine which task should handle them. The MIB API is used by the OBC for two reasons. These are encoding structures like housekeeping, telemetry, and telecommands into serialized data as well as decoding serialized data into structures.

Parameter Database

The parameter database (paramdb) is used for keeping important information that must be recoverable in case the OBC has a scheduled or an unexpected reboot. This data includes for example the MSP sequence flags. Paramdb uses the OBS API to store the information in FRAM.

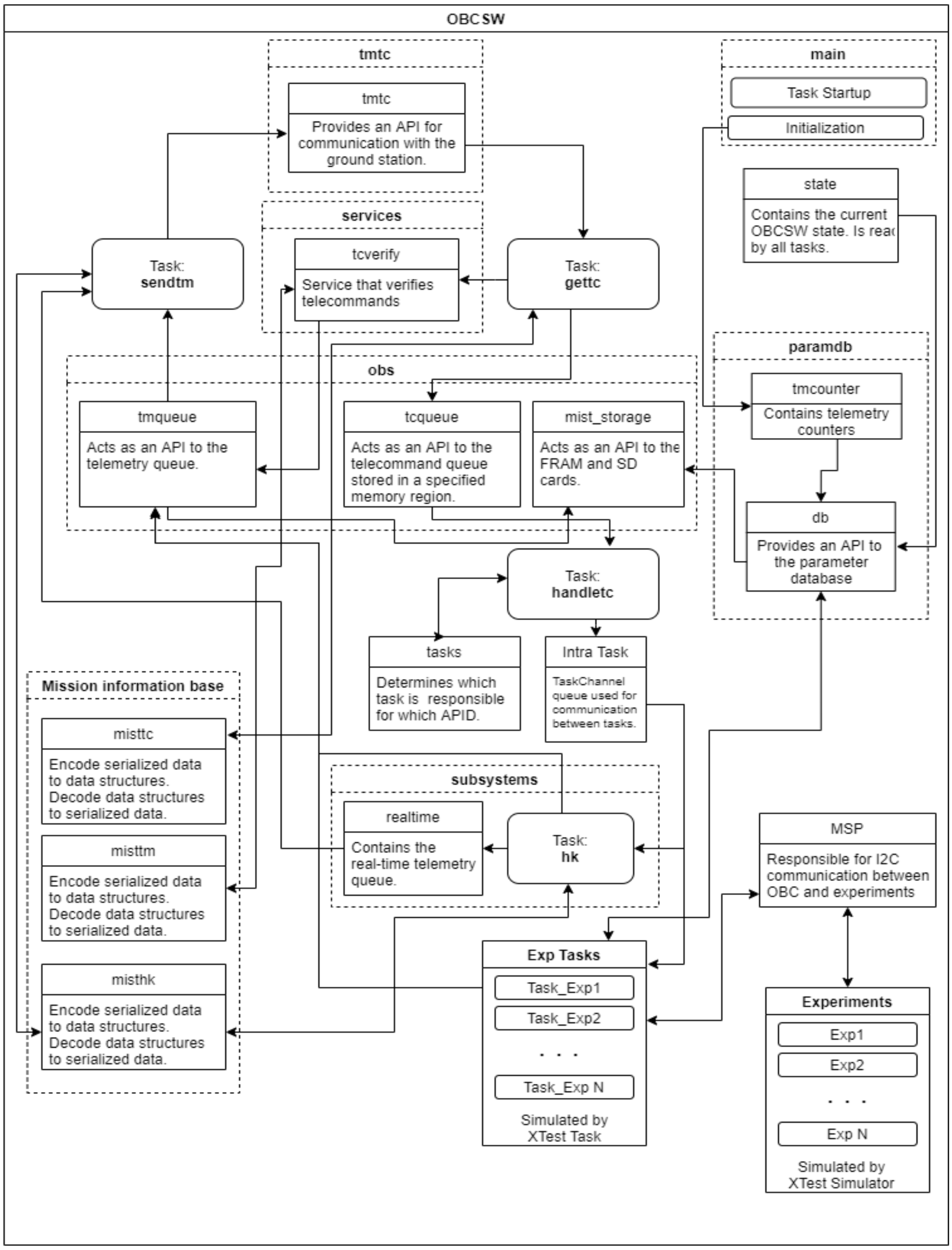

Figure 23 The tasks and the data flow of the MIST on-board software.

Tasks

Initialization task

The initialization task's main goal is to initialize the framework. It runs only once on startup before all other tasks and then terminates itself, allowing all other tasks to run in the process. The initialization task consists of the pre-initialization, initialization phase, and the post-initialization. The pre-initialization is responsible for the startup of the hardware subsystems that are vital for the initialization phase, which includes I^{2}C, FRAM, the clock, and the watchdog. When hardware initialization has been completed the actual initialization phase is run which sets up the satellite itself by, for example, de-tumbling the satellite. Once this is done the post-initialization starts which is responsible for the startup of the remaining functionality, such as the SD-cards, telemetry and telecommand queues, TMTC API, and the queues for the communication between the tasks.

GetTC task

The GetTC task is responsible for retrieving the telecommands from the TRXVU radio by polling it periodically. There are two types of telecommands which can be received, time-tagged and immediate. If the fetched telecommand is of type immediate, it will be executed immediately after fetching, either by GetTC directly or by the corresponding task. Otherwise, it will be inserted into the telecommand queue for later execution. One type of immediate TC is to set the telemetry modes to either "Out of range", "Near Horizon" or "Over GS" to adapt the telemetry types sent depending on the position during the ground station pass.

If any TC that is sent and is to be acknowledged as accepted to the ground station GetTC will create an ack-telemetry to be sent back to the ground station by the TMTC API.

HandleTC task

The HandleTC task is responsible for handling all telecommands stored in the telecommand queue by the GetTC task and forward it to the correct task at the correct time. It polls the queue periodically to check for entries in the queue that are ready for execution, meaning its time-tag has been reached. It then forwards it to the appropriate task determined by its APID. Once the telecommand has been forwarded, it is to be executed immediately by the corresponding task as no other tasks will handle the timing behavior.

SendTM task

The SendTM task is responsible for fetching telemetry from the telemetry queues and sending it to the ground station via the radio. It schedules the telemetry queues and the real-time telemetry queue based on the current OBC state and polls each one according to the schedule until it finds telemetry to send. It then repackages the telemetry using encoding from TMTC API to convert the data into the correct structure with the needed additional headers for the TRXVU to use. It will then send the telemetry to the ground station via the TRXVU radio. It uses the parameter database to store the telemetry frame sequence counter to be able to restore and achieve proper resumption in case of an OBC reboot.

HK task

The HK task is responsible for gathering housekeeping data from various subsystems and storing it in the real-time telemetry queue to eventually be handled by the SendTM task. This housekeeping data will be collected regularly to monitor subsystems like the radio and the OBC supervisor and detect issues.

XTEST task

XTest is a task that is used to test the functional requirements of other experiments. It can be used to both create a template for the common basic functionality of all experiments as well as test and verify the unique requirements of any experiment. The task can easily be expanded to test, for example, requesting any size of data at any interval or to send commands for action to be performed by the intended simulator. Its main objective is to help to produce solutions and code which can be reused for all the other experiments and easily ported when the actual experiment is to be connected. It is polling the message queue periodically to check for new incoming telecommands. It will then examine it to determine what kind of telecommand it is.

There are currently two modes supported. Sending data and receiving passthrough data. Passthrough data are requests where the data is simply forwarded as-is from the experiment and then repackaged as telemetry and inserted into the corresponding queue to eventually be handled by SendTM task and sent back to the ground station. Sending data on the other hand is a type of telecommand where the task is sending data to the intended experiment. This data can in turn contain, for example, information or an instruction that may also have acknowledgment parameters that indicate whether the command is to be acknowledged once executed. The communication protocol used between OBC and experiments is MSP and it has error handling to make sure that all data is received correctly.

Telemetry transmissions

Fixed Limitations of telemetry and telecommand transmissions

Table 3: Telemetry and telecommand limitations derived from the TRXVU subsystem.

Description	Value
Maximum downlink bitrate	9600 bit/s
Maximum uplink bitrate	1200 bit/s
Downlink buffer capacity	40 frames
Uplink buffer capacity	40 frames
Downlink overhead	41 bytes/packet (AX.25 & CCSDS PUS only)
Uplink overhead	32 bytes/packet (AX.25 & CCSDS PUS only)
Maximum downlink payload size	214 bytes
Maximum uplink payload size	188 bytes

The maximum number of different arrangements of housekeeping parameters that can be transmitted to the ground station is 256. This is due to that Elveti[7] follows the CCSDS PUS

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[7] The Mission Control Software (MCS) used by MIST.

standard which uses a single byte to determine the structure of the received housekeeping packet.

Definitions

Telemetry (TM) is defined as data transmitted from the satellite. Traditionally it is split between "housekeeping telemetry" and "payload (experiment) telemetry". By "housekeeping" (HK) it is usually meant to mean "health" signals from, mostly from subsystems; data such as voltages, currents, temperatures, switch settings, etc. Experiments (payload telemetry), may also have HK TM but that is usually embedded in the science data - as it is on MIST.

An issue with this split is that telemetry such as telecommand acknowledgments (CCSDS PUS service type 1) and test pings (CCSDS PUS service type 17) do not seem to fall into either of these categories. A second proposal was to split telemetry into "Subsystem Housekeeping", "Experiment Housekeeping", "Experiment Data", and "Systems Telemetry". The Systems Telemetry category would encompass all telemetry data used by the ground station and satellite to communicate on a systems level, such as verifying that a telecommand arrived safely on the satellite.

A *mode of operation* is a state of the on-board software that determines the behavior of the system. An example of a mode of operation is the initialization mode which is the first mode that is entered after MIST has left the launcher.

Elveti telemetry capabilities

Elveti provides a lot of support for the HK, we shall stick to CCSDS PUS service type 3 to make use of it. Elveti has a format of the HK parameters where they are preceded by 1B of ID & value type (signed/unsigned, enum etc). This puts a limitation of max 213 bytes of housekeeping parameters packed together in a single frame.

Dimensioning experiment telemetry

- **NanoProp**: We shall treat it separately from all other experiments. NanoProp (NP) generates lots of data over a 30 minutes run, we can sample some of it over the ground.
- **CUBES** will generate 8 kiB of histogram data every 60 seconds under a period of 24 hours. This 8 kiB is estimated to be the combined size for data from both CUBES1 and CUBES2.

Collection of housekeeping telemetry

It has been estimated that to collect stored HK every 5 minutes, around 11kB per day (M154-034v2, §3.3) is adequate.

Telemetry Queues

Three queues for experiment data are contemplated: One for CUBES histograms, one for the Camera, and one for the rest of the experiments. The data generated by the non-CUBES-or-Camera-experiments are expected to be small enough such that it would not block the queue.

Telemetry in normal and safe mode situations

This section contains a simple sketch over which telemetry to send at a certain stage of a ground station pass. During a single day we expect to have 6 "good passes" (15°-20°) and 4 "bad passes" (0^{o}-5^{o}). This does not touch on what data to generate, only what data to send if it is available at the time of the pass.

Normal situations

Telemetry group	**Near the horizon (2°-7°)**	**Over the G/S (7°-90°)**
Basic Overall HK (stored & RT)	**Yes**	**Yes**
Extended Overall HK (stored & RT)	No	No
Acceptance Reports	**Yes**	**Yes**
Experiment Data	No	**Yes**
System Communications	No	**Yes**
Current Configuration	No	**Yes**

Safe mode situations

Telemetry group	**Near the horizon (2°-7°)**	**Over the G/S (7°-90°)**
Basic Overall HK (stored & RT)	**Yes**	**Yes**
Extended Overall HK (stored & RT)	**Yes**	**Yes**
Acceptance Reports	**Yes**	**Yes**
Experiment Data	No	**Yes**
System Communications	No	**Yes**
Current Configuration	No	**Yes**

Scheduling of telemetry

This follow-up session resulted in a scheduling policy of telemetry that is based on a round-robin method. To formalize this policy, the concepts of "telemetry source" and "telemetry mode" must be introduced.

Telemetry Source

A telemetry source from the perspective of the scheduling policy is an interface in which the task that manages the transmission of telemetry in the on-board software can use to access telemetry from a particular group. This interface must fulfil 2 properties: the ability to check if telemetry is available and to retrieve telemetry when it is available. Examples of telemetry sources are a tmqueue from the obs-api[8] or real-time telemetry stored in RAM memory.

Telemetry Mode

A telemetry mode is defined in terms of a fixed set of telemetry sources $S = \{s_0, s_1, \ldots, s_{n-1}\}$ that are shared between all telemetry modes. This set is predetermined and will never change during the entirety of the mission. A telemetry mode m is a function $m : S \to \mathbb{Z}_{2^{32}}$ where $\mathbb{Z}_{2^{32}} = \{0, 1, 2, 3, \ldots, 2^{32} - 1\}$. The output of $m(s_i)$ should be interpreted as the number of telemetry packets to send from the source s_i.

Scheduling Policy

A scheduling policy is a simple round robin procedure that operates on a telemetry mode m. The procedure works as follows:

---

[8] https://gitlab.com/kth-mist/obs-api

```
for i in 0 to n-1 do
    for j in 0 to m(sᵢ) do
        if sᵢ has packet then
            send packet from sᵢ
    done
done
```

This procedure is to be executed as part of the sendtm task in the on-board software. How frequently this procedure should be performed is not yet decided, but there should be some delay between each invocation to allow other tasks in the on-board software to run.
To illustrate how this procedure works with an example, consider this telemetry mode:

$$m(x) = \begin{cases} 1 & if\ x = s_0 \\ 0 & if\ x = s_1 \\ 3 & if\ x = s_2 \end{cases}$$

This mode tells us that each time we run the scheduling procedure, we should first send one packet from s_0, no packets from s_1, and lastly 3 packets from s_2.

Modes of On-board Software Operation

A mode of operation in the on-board software is a state that determines how the OBC should behave in a specific situation. An example of such a situation is how telemetry should be sent where the mode of operation determines the telemetry mode to be used. More specifically, a mode of operation has 3 modes of telemetry for when the satellite is

- near the horizon of the GS (2°-7°),
- over the GS (7°-90°), and
- out of range (below 2°).

These telemetry modes should be possible to trigger by time tagged telecommands. It should also be possible to modify a telemetry mode by telecommand such that the modifications become active the next time that telemetry mode is triggered. Apart from triggering a dedicated telemetry mode from the current mode of operation, it should also be possible to manually override the current telemetry mode by telecommand.

Preliminary Table of On-Board Software Modes of Operation

This section provides a table over the currently conceived modes of operations. The trigger for any individual mode of operation can either be an internal measurement, such as battery voltage, or an immediate telecommand. It is not possible to trigger a mode of operation by a stored (time tagged) telecommand.

Name	Description
Initialization	The first mode that is entered after the satellite has been deployed from the launch vehicle. Handles deployment of solar panels, antennas, etc.
Commissioning	Initial contact with satellite in orbit after launcher deployment. Look at HK and run diagnostics to make sure that everything looks OK.
Safe	A mode that is entered when the state of the system is uncertain. This is the default mode that is entered after an unexpected reboot. It is not possible to transition from this mode until $V_{batt} \geq V_{normal}$.
Troubleshooting	Essentially the same mode as Safe Mode, except that there are fewer restrictions on what is allowed. In this mode it is allowed to turn on specific subsystems or experiments to run diagnostics on what might have gone wrong.

Name	**Description**
Mission	The mode of the on-board software where experiments are being run. This is the default mode that is entered after a scheduled reboot.

Table 4 Onboard software modes

Housekeeping Telemetry Groups

The housekeeping telemetry groups are divided into smaller subsets. The *Basic HK* group will be split into smaller subsets that only contain:

- EPS HK (Full),
- System HK (OBC software state),
- iOBC supervisor HK,
- TRXVU HK (Full),
- AntS HK,
- Solar Panels HK, and
- iMTQ HK (Full, no Eng.).

The telemetry group *Full Basic HK* should then be the union of all these subsets. The same treatment is also given to the *Extended HK* group.

Data storage and transmission overhead

Assume that we want to store X bytes polled from an experiment or subsystem in the SD-card and then transmit it to the ground station.

- The overhead on the SD-card storage is then: 9*ceil[9](X/212) Bytes
- The overhead on the downlink is 43*ceil(X/212) Bytes.

The overhead on the storage in the SD-card is relatively benign. The AX.25 downlink data field in MIST is 214 B long, but we have added 2B to be sure we can implement packet sequence control in case the experiment data polls are longer than that fit into one AX.25 packet. Clearly the overhead on the downlink is substantial, especially for small data polls from experiments. Table 5 below shows how experiments will be operated and data collected from them. Clearly, the CUBES experiment requires most of the capacity.

Exp#	**ON interval**	**On period**	**Active period**	**Cycle period**	**Poll interval/fx**	**Bytes/Poll**	**Notes**
CUBES	=ON	24 h	24 h	7 days	60 s	3472 B	Per CUBES unit
LEGS	1 orbit	≈22 min	24	7 days	≤ 1300 s	16 B	OFF at eclipse
NanoProp	7 orbits	30 +10	≤ 24 h	Several	5 s, 5 Hz	4 B, 240 B	≤ 2 ON/day
SEUD	∞	∞	∞	∞	≈600 s	28 B	Continuously
SiC	3600 s	1 s	∞	∞	3600 s	64 B	
Camera	≥24 h	≤ 5 s	∞	∞	≥ 24 h	-	Not via I2C link

Table 5 Experiment data collection details

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[9] Ceil(y) is the ceiling function, i.e. the least integer greater than or equal to y.

The definition of the times in the table is given in Figure 24.

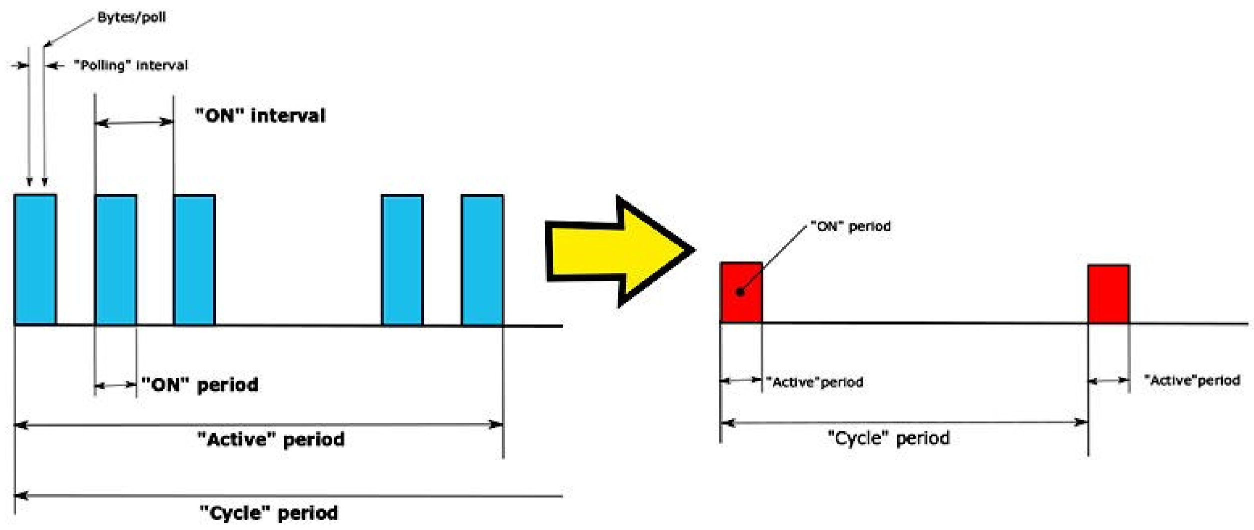


Figure 24 Data collection timing definitions.

2.2.5 *Telemetry, Tracking and Communications (TT&C) subsystem*

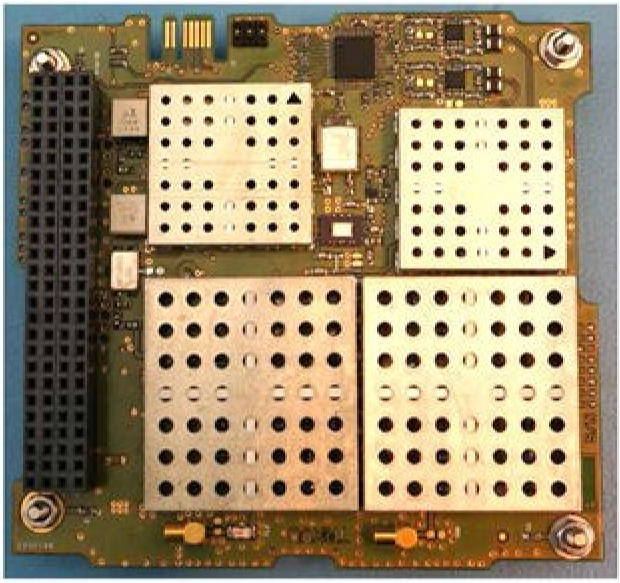


Figure 25 The TRXVU transceiver board.

The TT&C subsystem on MIST consists of a transceiver and an antenna system. Early in the project it was decided to use a “full duplex” radio system, which means that it transmits and receives on different frequencies. The reason for this choice was to maximize the downlink data rate by not interrupting the downlink while transmitting commands.

The procurement process for basic subsystems led to the selection of the ISIS TRXVU transceiver that receives on VHF (145.86 MHz) and transmits on UHF (437.405 MHz). The data rate on the uplink is 1.2 kbps and the maximum data rate on the downlink is 9.6 kbps. The modulation on the uplink is AFSK (3.5 kHz deviation) while the downlink uses BPSK. The transmitter power at the TRXVU output is 0.5 Watts. The DC power consumption is about 3 W. The TRXVU is not equipped for forward error correction. The unit weighs about 75 g.

The ISIS **deployable antenna system** (AntS) contains up to four shape memory alloy tape antennas of up to 55 cm length, which deploy from all four sides of the structure upon command from the iOBC via the I^{2}C data bus. The antenna elements may be set for configurations (4 x monopole, 2 x ¼-wave dipoles or 1 x turnstile). For MIST AntS is configured for two dipoles one for VHF and one for UHF. AntS weighs less than 90 g.

The antenna system consists of up to four antenna elements which are rolled-up and stowed inside the antenna housing. An aluminum bracket creates an enclosure in which the antenna is stowed and contains a Polycarbonate lid to release and deploy the antenna in orbit. The antenna elements are made out of a NiTi-alloy based shape memory alloy.

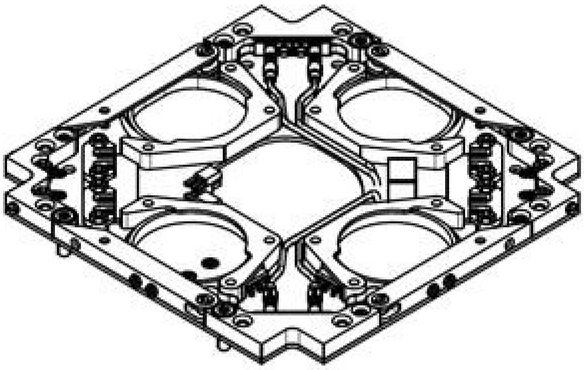


Figure 26 The inside of AntS, showing the four rolled-up antenna elements and the hole in the middle where cables are routed to the "lower stack".

The lid is kept close with a spring tensioned burn wire which is made from Dyneema wire. The wire is routed over a set of redundant resistors which are heated on command, which melts the wire and releases the lid. The AntS is shaped like a square unit about 6 mm thick and in MIST is mounted “below” the subsystem stack. AntS is mounted so that no cables can run on the outside of the unit. Therefore there is a hole in the middle of AntS through which cables are routed. This is also where the coaxial cables from the TRXVU are connected to AntS. As can be seen in Figure 15 the short UHF transmit antenna dipole is located under the deployable solar panels while the VHF receive antenna dipole is perpendicular to the transmit dipole.

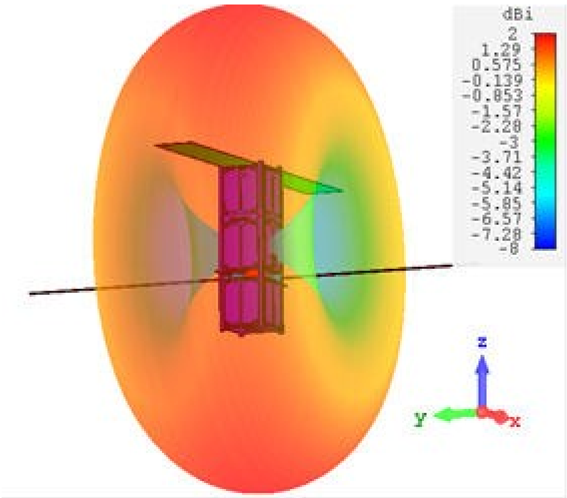


Figure 27 Radiation pattern for the receive antenna.

Radiation pattern simulations have been performed as part of a B.Sc. thesis. From these diagrams (see Figure 28 and Figure 27) it seems reasonable to assume an antenna gain of 0 dBiL in link budgets for both up and downlink. The ground station antenna has to take into account that both the receive antenna and the transmit antenna on the satellite are linearly polarized. The ideal solution would have been to provide polarization diversity, i.e. a ground antenna system that “tracks” the polarization plane of the downlink signal, but this represents a huge increase in complexity. Therefore, circular polarization has been chosen for the ground station receive antenna – even if this choice comes with a penalty of a 3 dB polarization loss. The ground station transmit antenna will also be circularly polarized.

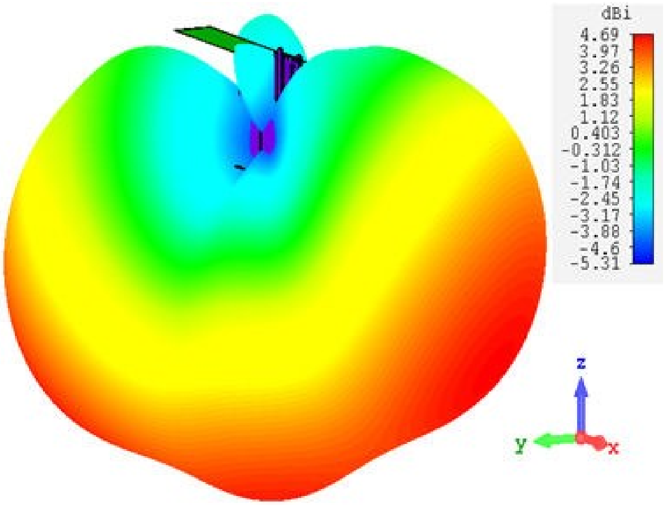


Figure 28 Radiation pattern for the UHF transmit antenna. The solar panels lie in the orbital plane.

The MIST transceiver is a proven design with flight heritage, but it has a drawback in that it does not support forward error correction on the downlink. In addition, it can only support a downlink data rate of up to 9.6 kbps. The design of the radio link therefore needs to show that a downlink data rate 9.6 kbps can achieved during almost an entire ground station pass. As is standard in the space industry a minimum elevation angle of 5° is assumed in link budgets. It is important that a good link margin is maintained even at low elevation angles since the satellite spends most of its time over the radio horizon at low elevation angles.

Initial link budgets developed in the project were based on the need to maintain a 6 dB link margin. It was felt that this was necessary to compensate for the not-perfect antenna diagram of the satellite and other factors such as man-made local interference at low elevation angles. The conclusion of those initial analyses was that the ground station needed an antenna gain at the downlink frequency 437 MHz of almost 25 dBiC. This corresponds to four crossed Yagi antennas fed in phase. Each Yagi antenna would be 5 meters long. Such an antenna system is large, heavy and creates high wind loads on the rotator device and on other parts of the antenna installation.

The link budgets have been revisited by students taking into account B.Sc. thesis on the ground station design for both the SEAM and MIST satellites as well as advice from RF and ground station experts at our subsystem supplier ISIS. An important change in the link budgets was to reduce the link margin from 6 dB to 3 dB on the advice of ISIS.

The assumptions in early link budgets indicated a link margin of almost 9.5 dB at 5° elevation. Therefore it was possible to contemplate a 6 dB reduction in the link margin and a corresponding reduction in the antenna gain of the ground receiving antenna. Therefore, the new baseline is to use only one 5 meter long UHF antenna for reception – greatly reducing the wind loads and making installation of the station easier.

Parameter	Value	Units
Spacecraft		
Spacecraft Transmitter Power Output:	0.5	watts
In dBW:	-3.01	dBW
Spacecraft Total Transmission Line Losses:	0.70	dB
Spacecraft Antenna Gain:	0.00	dBi
Spacecraft EIRP:	-3.71	dBW
Downlink Path		
Spacecraft Antenna Pointing Loss:	0.00	dB
S/C-to-Ground Antenna Polarization Loss:	3.00	dB
Path Loss:	153.01	dB
Atmospheric Loss:	2.10	dB
Ionospheric Loss:	0.40	dB
Rain Loss:	0.00	dB
Isotropic Signal Level at Ground Station:	-162.21	dBW
Ground Station (Eb/No Method)		
Ground Station Antenna Pointing Loss:	0.23	dB
Ground Station Antenna Gain:	18.90	dBi
Ground Station Total Transmission Line Losses:	1.77	dB
Ground Station Effective Noise Temperature:	524.00	K
Ground Station Figure of Merrit (G/T):	-10.07	dB/K
G.S. Signal-to-Noise Power Density (S/No):	56.09	dBHz
System Desired Data Rate:	9600	bps
	39.82	dBHz
Telemetry System Eb/No for the Downlink:	16.27	dB
Demodulation Method Seleted:	**D-BPSK**	
Forward Error Correction Coding Used:	**None**	
System Allowed or Specified Bit-Error-Rate:	1.0E-05	
Demodulator Implementation Loss:	2.00	dB
Telemetry System Required Eb/No:	10.80	dB
Eb/No Threshold:	12.80	dB
System Link Margin:	**3.47**	dB

Table 6 MIST downlink budget.

The link budgets reproduced here have been derived from the IARU spreadsheet available on-line. The link budgets are computed for 5° elevation angle and an assumed spacecraft antenna gain of 0 dBi even if the normal gain in the direction of the ground station may be 2-3 dBi. By using 0 dBi as the spacecraft antenna gain expected attitude variations from nadir pointing of up to 20°-30° are assumed. In a tumbling situations complete loss of up- and downlink link margin can be experienced for brief periods.

It should be emphasized that the uplink margin at the horizon should be computed against the sensitivity of the onboard receiver which is -105 dBm. The received signal level is -120.87 dBW, i.e. -90.87 dBm, so the link margin is -90.87-(-105)=**14.13** dB

Parameter	**Value**	**Units**
Ground Station		
Ground Station Transmitter Power Output:	100.0	watts
In dBW:	20.0	dBW
Ground Stn. Total Transmission Line Losses:	3.24	dB
Antenna Gain:	12.34	dBi
Ground Station EIRP:	29.11	dBW
Uplink Path		
Ground Station Antenna Pointing Loss:	0.07	dB
Gnd-to-S/C Antenna Polarization Losses:	3.00	dB
Path Loss:	143.47	dB
Atmospheric Losses:	2.10	dB
Ionospheric Losses:	0.70	dB
Rain Losses:	0.00	dB
Isotropic Signal Level at Spacecraft:	-120.20	dBW
Spacecraft (Eb/No Method)		
Spacecraft Antenna Pointing Loss:	0.0	dB
Spacecraft Antenna Gain:	0.0	dBi
Spacecraft Total Transmission Line Losses:	0.67	dB
Spacecraft Effective Noise Temperature:	1997.49	K
Spacecraft Figure of Merit (G/T):	-33.67	dB/K
S/C Signal-to-Noise Power Density (S/No):	74.7	dBHz
System Desired Data Rate:	1200	bps
In dBHz:	30.8	dBHz
Command System Eb/No:	43.94	dB
Demodulation Method Selected:	**AFSK/FM**	
Forward Error Correction Coding Used:	**None**	
System Allowed or Specified Bit-Error-Rate:	1.0E-05	
Demodulator Implementation Loss:	1.0	dB
Telemetry System Required Eb/No:	19	dB
Eb/No Threshold:	20.00	dB
System Link Margin:	**23.94**	dB

Table 7 MIST uplink budget

Figure 29 shows how the uplink margin changes during a typical pass close to the ground station.

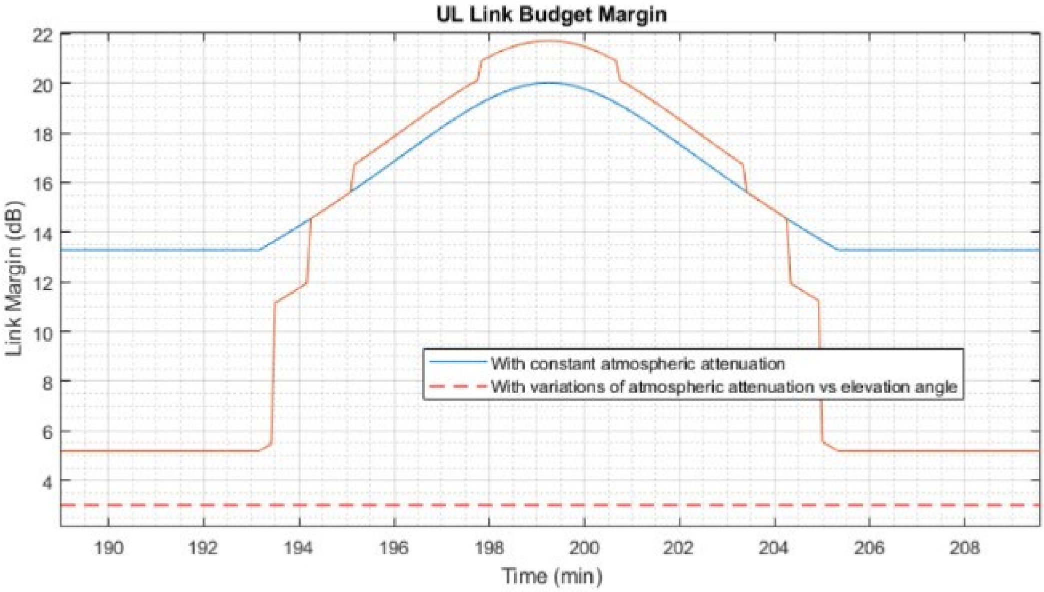


Figure 29 Uplink margin for a typical pass over the ground station.

2.2.6 *Structures and Mechanisms*

A decision was taken very early in the project to not build a custom-made structure for MIST. This would have necessitated extensive structural analysis and the construction of a structural qualification model with representative mass dummies. Instead the standard ISIS structure (Figure 30) was selected and the standard method of attaching printed circuit boards to the structure was chosen. In this way the need for a separate structural analysis was avoided.

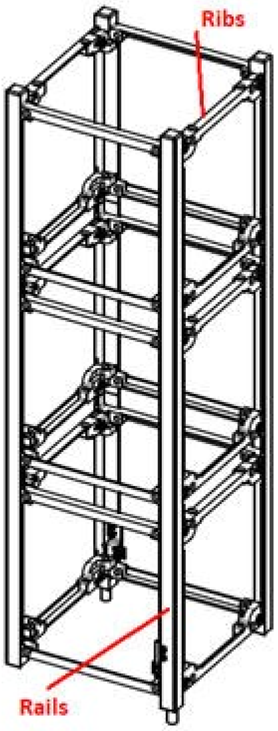


Figure 30 Standard structure.

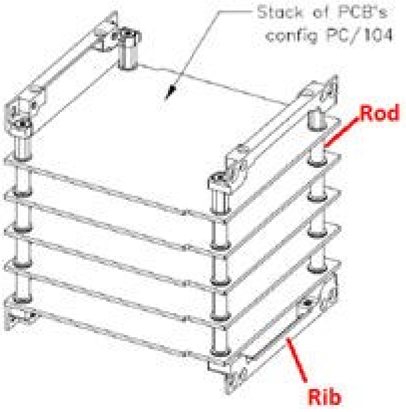


Figure 31 A PCB stack.

3 The structure is rather weak, but this is possible because it is supported by the deployer mechanism during the launch. The rails form the contact surfaces with the deployer. Printed circuit boards are connected by "rods" that are mounted on "ribs" that connect the "rails". (Figure 31)

There are two mechanisms on MIST, the antenna system AntS and the HDRM (Hold-Down and Release Mechanism) for the solar panels. The AntS is described in section 2.2.5. It is a standard subsystem manufactured by ISIS.

The HDRM, also a standard unit from ISIS, is a purely mechanical system for releasing the deployable solar panels that contains two burn wires and an electrical interface to the on-board computer daughterboard. Switches on the daughter board send voltage to burn wires that release the solar panels. The board does not include any control logic; however, it does contain two physical switches from which it is possible to read back the state of deployment. The control logic of deployment (sequence, burn time, etc), is done at software level by the on-board computer. The board consumes 2 W while burning the wires (at 5 V).

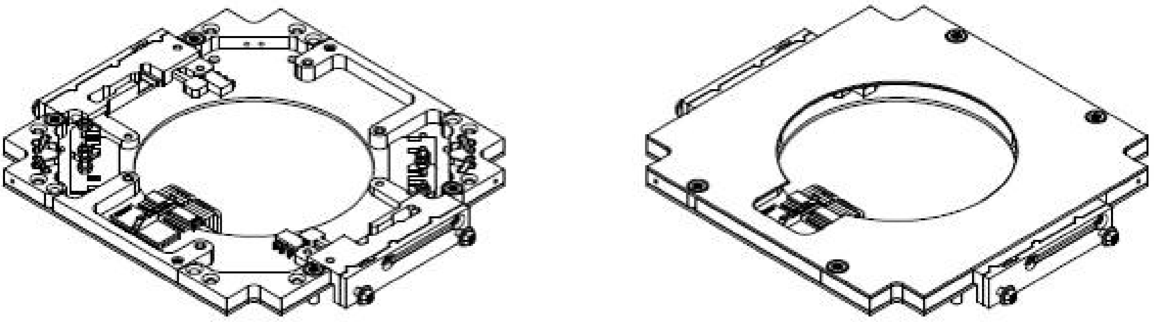


Figure 32 HDRM system, with cover hidden (left side) and cover shown (right side)

2.2.7 *Thermal control*

The high number of experiments on MIST (initially there were two more than in the present configuration) and the need to provide sufficient power to run all experiments led to a total

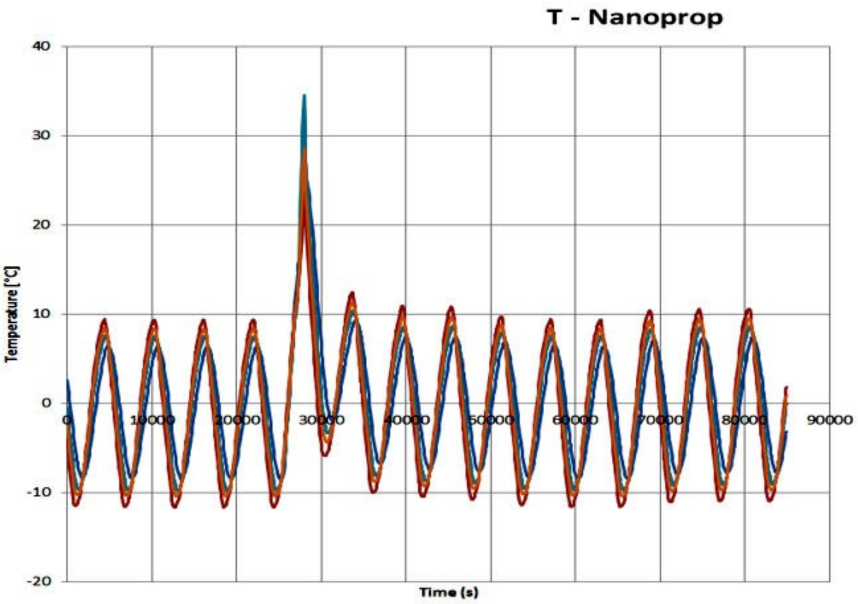


Figure 33 Temperature variations of Nanoprop after the change of accommodation. Cold case. As can be seen by the temperature increasing at exit from eclipse the sun is used to reach proper operating conditions later during the sunlit period.

lack of area to install radiators. Also, the very tight space behind solar panels also prevents the installation of multi-layer insulation. The demand for power to run the experiments and also leads to a lack of power to provide heaters to keep experiments warm enough – except for the battery that has a built-in heater. All this means that only a few tools are available for the thermal designer. In MIST, experiments dissipating much power can be placed close to those that don't, titanium washers can be used to avoid heat conduction into areas of concern. There are a few areas that are not covered by solar panels. They can be covered with thin aluminum sheets with appropriate coating to regulate the temperatures of units behind them.

The sun is used to provide proper operating conditions for those experiments that only operate for times shorter than the orbital period. The Nanoprop unit is therefore operated only in sunlight and by reducing the size of the butane tank to the standard height it was possible to avoid that it protruded from the satellite body and "viewed" the sky getting very cold in eclipse and hot in sunlight. By now containing the experiment completely inside the satellite body and providing a top cover (with openings for thruster plumes) and adding titanium washers at the interface to the main structure the temperature fluctuation of Nanoprop (Figure 33) is now foreseen to be much less than previously feared. It is turned on when the temperature exceeds 0°C – the operational lower limit. The peak temperature is well below the +50 °C limit.

The MIST project uses Airbus' Thermica (Parts of the Systema suite) for thermal analysis.

		Non-operational temp. [°C]		**Operational temp [°C]**	
		Min	Max	Min	Max
Subsystem	TRXVU	-40	60	-40	60
	Solar Panels	-40	100	-30	70
	Battery	-5	45	-5	45
	EPS	-40	85	-40	85
	IGIS	-30	70	-30	70
	Antenna System	-50	85	-20	60
	Magnetorquer	-40	70	-40	70
	OBC	-40	80	-25	65
Experiment	Camera[10]	0	70	-30	70
	SiC	-40	105	-40	105
	SEUD[11]	-65	150	0	85
	NanoProp	-10	50	0	50
	LEGS	-30	70	10	40
	Cubes[12]	-20	60	-20	30

Table 8 Operational and non-operational temperature limits.

---

[10] stable image: 0 - 50 °C

[11] operational Artrix7 circuit: -40 - 100 °C

[12] unpowered: -20 - 80 °C

2.2.8 Propulsion (when applicable)

See section about the Nanoprop payload in section 2.2.1. The Nanoprop propulsion system made by Gomspace is a qualified, flight-proven system.

2.2.9 Grounding Scheme (EMC/EMI)

As common in CubeSats, MIST has distributed grounding – the satellite structure is the reference for all voltages in the satellite, and all electronic equipment are connected by more than one point to the chassis.

No specific aerospace standards cover set requirements for the twisting and braiding requirements on CubeSats. In consultation with other CubeSat suppliers and aerospace experts MIST has chosen to adhere to the following general practices for twisting (~3 twists per cm) and braiding in order to reduce electromagnetic interference/ inducing currents in surrounding circuits and minimize harnessing volume.

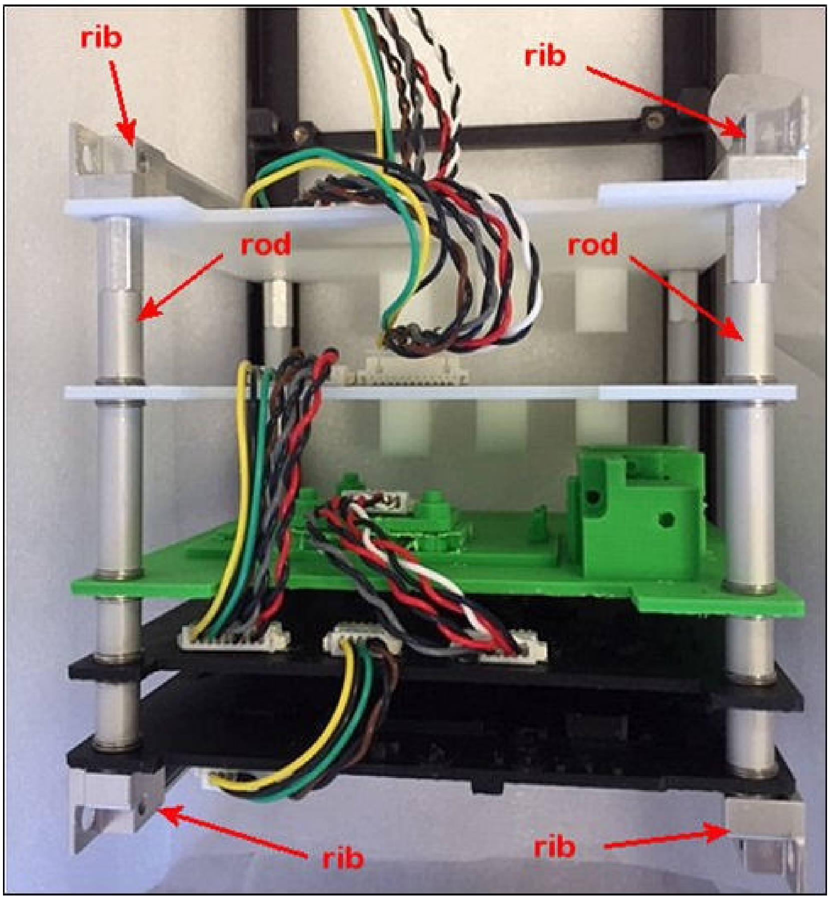


Figure 34 Mock harness installed on 3D-printed bottom stack mock-up experiments

In designing experiments a conscious effort has been undertaken to minimize magnetic materials in order to keep the overall magnetic dipole moment low and avoid perturbing the attitude control function.

2.2.10 Ground Segment

Location

The idea is to use the “ventilation fan house” on top of the building at Teknikringen 29 on KTH’s main campus in Stockholm, Sweden as the location for the ground station antenna. This is an extension on top of the building with brick and concrete walls. The Transceiver, the ground station computer, and the Mission Control computer will be located in a nearby office in the top floor of the building.

The antenna system will be attached to the northern wall of the “fan house”, a wall that is made of reinforced concrete. Figure 35 shows how the antennas are mounted on a mast connected to a stiff lattice tower. The antennas are shown pointing vertically.

Low-noise amplifier and bandpass filter

The urban environment where KTH is located is electromagnetically “noisy”. Relatively strong RF carriers in the neighborhood have been found near the receive frequency for MIST. It is therefore important to have a low-noise amplifier (LNA) with good third-order intermodulation characteristics. An analysis of a receiving system using an LNA based on the PGA-103+ device shows that the resulting intermodulation products are harmless in the RF environment near the downlink frequency. But this conclusion is based an important prerequisite: There needs to be a bandpass or high-pass filter in front of the LNA with a high attenuation at the uplink frequency. A filter at the ground transmitter output is also needed to attenuate transmitter harmonics.

Antennas, wind loads, rotator and mast tube

For the UHF downlink the 436CP42UG antenna from M2 Antenna Systems with 18.9 dBiC gain has been selected and its performance used in the downlink budget. This antenna is circularly polarized. For the VHF uplink the 2MCP14 antenna from m2 Antenna Systems with 12.3 dBiC gain has been selected and its gain used in the uplink budget.

These antennas have been used in the calculation of the wind loads. A design wind speed of ≈45 m/s (Beaufort wind force scale number=14) has been used in all calculations. The maximum wind torques in elevation and azimuth are 410 Nm and 208 Nm respectively. The antenna rotator must be able to handle these torques in at least the braking mode, i.e. the antenna must not be rotated in any direction by the maximum wind. The selected rotator type is therefore the Alfa-Spid RAS (brake torque 1582 Nm, turn torque 366 Nm). It can almost operate normally at hurricane-strength winds! The maximum bending moment on the mast tube is estimated to be 525 Nm. An Aluminum 6061-T6 tube with 76.2 mm diameter and 6.4 mm wall thickness has sufficient strength to handle this bending moment and to deflect only 1 mm.

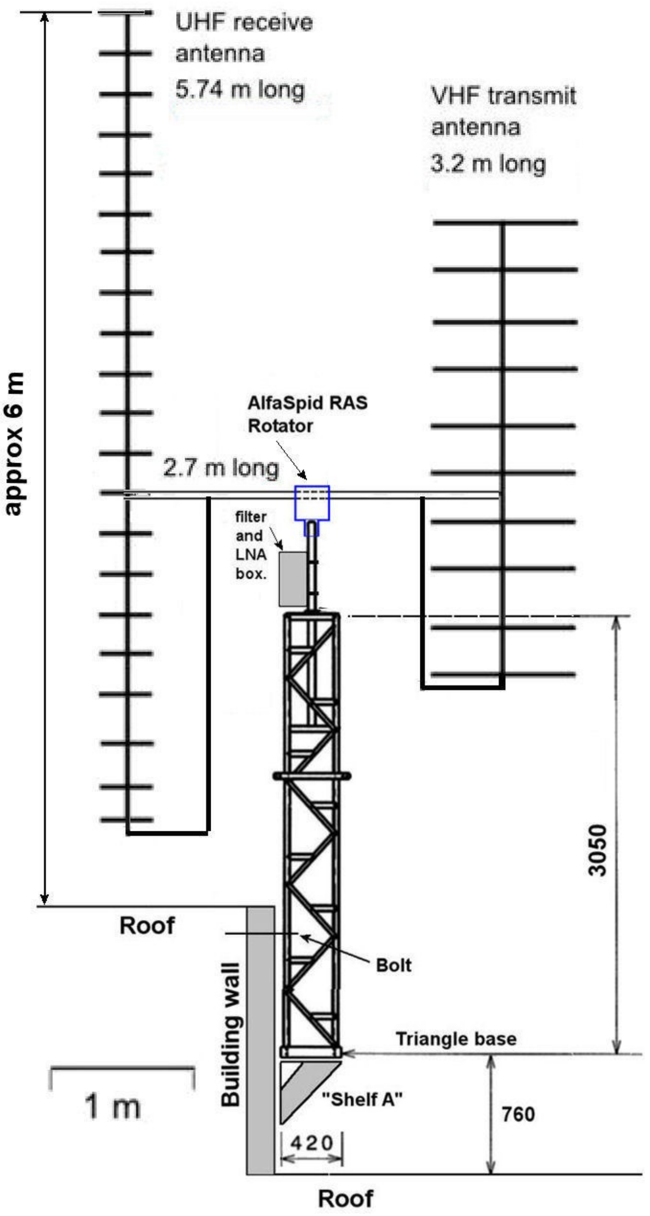


Figure 35 MIST Antenna site arrangement.

Mission Control Software

For running the satellite including the TRXVU radio in the lab without using a full ground station MIST uses the so-called RF Checkout Box which is essentially a “ground station” for laboratory use. It is equipped with a software-defined radio for both transmit and receive functions and it can communicate with the Elveti Mission Control Software (MCS) via a USB connection. Elveti is a product of Solenix and has its roots in the SwissCube and QB50 projects.

G/S transceiver and computer

Very early in the project a student performed a thorough analyses of the configuration of the ground station and proposed subsystems and software needed to realize the station. The design is based on collecting the “bits and pieces” from various vendors and integrating the system into a ground station by students. The ground station computer (”G/S computer” in the figure) and the equipment and software associated with it represents the key engineering effort to put together and make it work with the Elveti Mission Control Software (MCS) used in MIST. This is still a possible solution.

However, the interfaces between the MCS computer running Elveti and the RF Checkout Box are to identical to those of the corresponding functions in the “ISIS ground station”. An obvious possibility is to shorten development time for the ground station by procuring the ground transceiver and the computer running the software supporting the transceiver from ISIS. This is the solution that has been adopted and the Transceiver and G/S computer have been ordered form ISIS. Antennas, LNA, rotator, tower and mast will be bought from other sources. Figure 36 shows a block diagram of a station configured around the ISIS transceiver and G/S computer.

The “Predict” software in the G/S computer computes where the satellite will be and “Gsat” displays the current satellite position on a world map. The DGS server is responsible for satellite tracking and radio/rotator control.

The MCS computer will be co-located with the G/S computer.

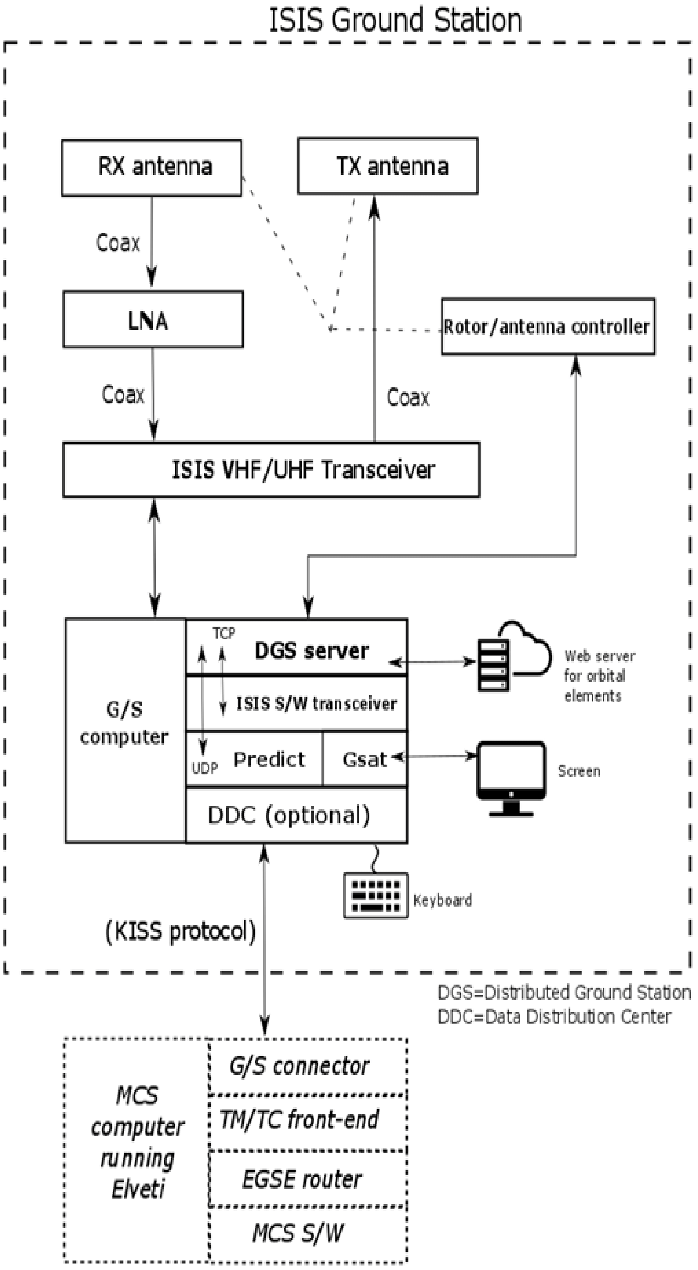


Figure 36 The MIST ground station based on the "ISIS ground station".

2.2.11 Technical Requirements Specification

See Appendix A.1 Technical Requirements Specification.

3 TECHNICAL CHALLENGES

The original experiment collection featured much different requirements regarding, power, voltages, operational profile, telemetry volume, thermal constraints, size, principle attachment to the satellite structure, viewing angles. Also, some experiments were defined as printed circuit boards while other experiments were more traditional "boxes".

The lowest temperature limits of some experiments were hard to satisfy because of the lack of power that could be used for heaters. The need to cover the outside of the satellite body with solar cells made it difficult, well impossible, to find room for radiative surfaces to use to dissipate excess heat to keep experiments below their maximum operating temperatures. The lack of thermal mass of the satellite leads to large temperature excursions.

Experiments with large data volume and power requirements led to the solution to divide experiments into "power groups", i.e. experiments operating together for certain periods of time – complicating the thermal analysis and, eventually, mission operations.

The fact that the satellite power system only has six switched low voltage (3.3 v or 5V) forced some experiments to share the same power switch, further limiting design flexibility.

The multitude of experiment has also forced the "daisy-chaining" of power and data communication lines. This is necessary because lack of room for running a multitude of cables in a "star" fashion and also because of installation ease of "daisy-chaining". However, it represents a risk in that one faulty connector in the beginning of the chain may deprive "downstream" experiments of power and data, but it is a necessary risk to take.

With the changes made to the experiment collection at the end of 2018 several of these accommodation problems have been much alleviated. Now all experiments except Nanoprop are basically printed circuit boards. Nanoprop is now located inside the structure which solves many of its thermal design issues. All other experiments are now located in the bottom stack which helps to create a relatively constant heat dissipation in that part of the satellite which creates a relatively stable thermal environment.

Many design tasks in the MIST project can be assigned to students that study Engineering Physics, Aerospace Engineering, Mechanical Engineering and similar disciplines. But the on-board software falls into a special category. Designing and writing such software is a rather specialized discipline using tools that the afore-mentioned disciplines normally do not teach. Students that work with the on-board software must be well versed in C programming, real-time operating systems and methods taught in “Embedded Systems” courses and applied to subjects such as “Mechatronics”. Project courses in these areas are structured in a rather well-defined form and often last less than a semester. This has both its advantages and disadvantages for MIST. The students work in a disciplined and structured way, but are recruited through teachers and not directly by the MIST team leader as in other areas. And the project courses are of limited duration, which provides efforts from students only in certain periods of the academic year.

A concern early in the project was that students with the skills need for the on-board software are located in Kista and not at the main campus. To remedy this two copies of the on-board computer were purchased and one was located at the Software and Computer Systems at Kista while the other was located at the KTH main campus.

4 ASSEMBLY, INTEGRATION AND VERIFICATION

4.1 Model Philosophy

The model philosophy selected for MIST is based on the fact that most of the units and subsystems that will fly on MIST have been qualified on unit level. This is true for all the basic subsystems, including the structure and the Nanoprop propulsion system. The remaining experiment are all located on boards that conform to the PC-104 standard. They can only be mechanically tested reliably when integrated into the real satellite structure.

This will happen in the shock and vibration tests on “protoflight” level, i.e. qualification level vibration levels at acceptance duration. So, they will be qualified in a system level test. This is reasonable because the size of the satellite is very similar to an electronics unit box on a larger satellite, where individual circuit boards are not vibration tested, but instead vibrated on “box” level. Of course there is a certain risk in not building qualification units for each circuit board and vibrating them in a specially designed fixture, but this risk is deemed to be small.

For thermal aspects experiments qualify their units on circuit board level. Experiments are free to make thermal test on circuit board level, otherwise their qualification status is achieved by thermal vacuum cycling on satellite level. A combined thermal balance/ vacuum cycling test on spacecraft protoflight level is planned.

The following models on system level will be used:

- **Engineering Model** – this model actually uses the flight structure for solving equipment accommodation issues and for harness development using 3D-printed replicas of all units and a flight-representative harness.
- **Bench Test Model** – for full-scale flight functional simulations with flight hardware aiming at verifying on-board software, all functional modes of the spacecraft, and interfaces with the ground segment.

  Initially experiments have been simulated with power drain simulators that are controlled in real time to reproduce the time dependence of experiment operation. Solar panel simulators connect to the EPS and faithfully mimic solar panel illumination taking orbital position, geometry, attitude, and earth albedo into account. Later the experiment simulators will be replaced by flight model experiments (or prototype boards) for verifying command and telemetry interfaces.

- **Protoflight model** – the assembled satellite used for environmental qualification testing as in Table 9.

Test	Proto-Flight
Acceleration (quasi-static)	Test planned
Vibration (resonance survey, sine and random vibrations.	Test planned
Shock	Test planned
Thermal-Vacuum, Balance	Test planned
Thermal Bake-out	Test planned

Table 9 Protoflight model tests.

4.2 AIV Activities

Engineering Model

A subsystem that was delivered from our supplier ISIS very early in the project was the structure and 3D-printing of all onboard units started immediately. The first assembly into the flight structure of all the mock units was done three years ago.

The routing principles of the harness was worked out by comparing CAD harness routing with experience from assembling and examining the assembled engineering model – as it is called in MIST. The conclusion from this activity was that it was impossible to find run data and power lines in a “star” fashion to each experiment. Instead the idea of “daisy-chaining” experiments was selected as the only feasible harness routing principle. In mid-2017 the first attempt at installing major pieces of harness on the engineering model was made.

Figure 37 First iteration of the Engineering model w/ 3D-printed experiments held by the team leader.

In early 2019 a major re-accommodation of experiments and 3D-prinitng of modified experiments was made and an effort made to produce a flight-representative harness. Solar panels were simulated by transparent Plexiglas sheets to

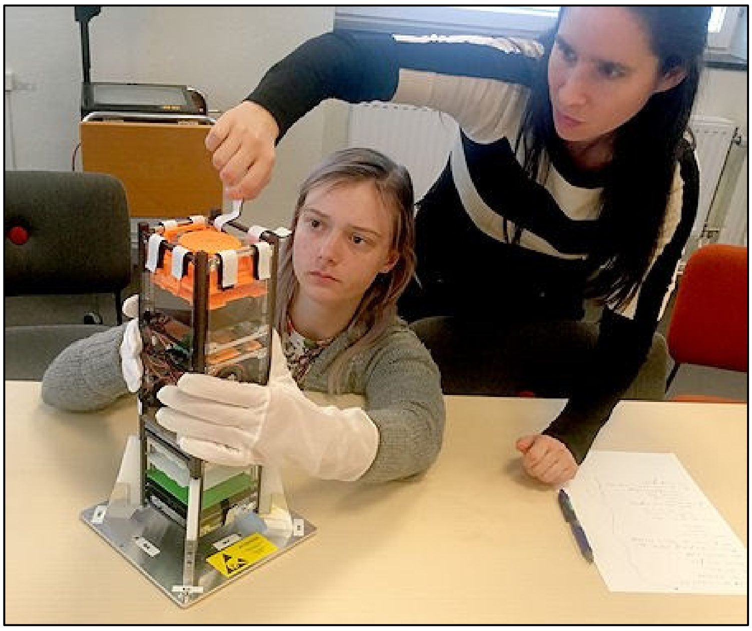


Figure 38 EM with complete mock units, flight-representative harness and Plexiglass panels to simulate solar panels demonstrated by students.

show how the harness runs behind them. The output of this activity was modified dimensions of harness elements, and a detailed assembly manual for the structure, units and harness.

Bench Test Model – Functional Testing

The Functional testing is the activity in the project aimed at verifying the satellite will work under all foreseeable condition once in orbit and in free flight. It culminates in flight simulations that aim at mimicking all flight phases and includes interactions with a ground station system identical in functionality as the real ground station.

The functional testing sequence builds up gradually to the full-scale flight simulation level from development of test equipment and tools, via basic tests on subsystem level, then basic on-board software testing followed by basic flight simulations. Figure 39 shows the plan and status of the functional testing. The basic flight simulations of the power system is the subject of a master thesis that was completed in the summer of 2019. Otherwise, the goal for the fall 2019 semester is to install the on-board software framework on the iOBC and start testing its basic functions (third column from the left).

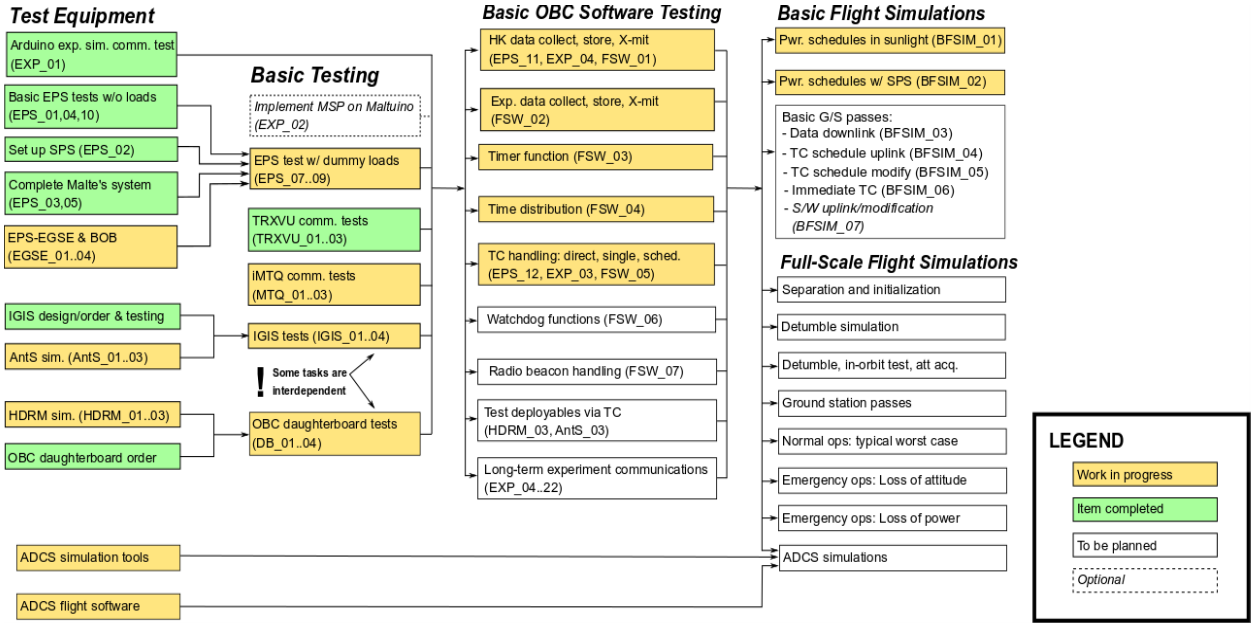


Figure 39 Phases and steps in functional testing

Power system flight simulations

Figure 40 shows the layout of the power system flight simulation environment. The “Flatsat” is the circuit board on which subsystems can be mounted side by side instead of vertically (as in the flight structure).

The “Maltuinos” (named after student Malte Gruber) are simulators for the power drain of each experiments and is controlled from a lap-top so that the power drain varies with time, in “simulated real-time” according to the preliminary flight operations schedule. They are connected via a “BOB” (break-out board) and the ground support equipment (EPS-EGSE) to the EPS on the "Flatsat". External power connections and I2C signals are also reached this way. Loads on switched power lines from the EPS can also be reached via the EPS-EGSE. The solar panel simulators (SPS) are controlled from the same laptop as the Maltuinos and thus operate on the same "simulated real-time" basis. The solar panel simulators were developed by a student and use algorithms also used to generate total power levels as described in section 2.2.3.

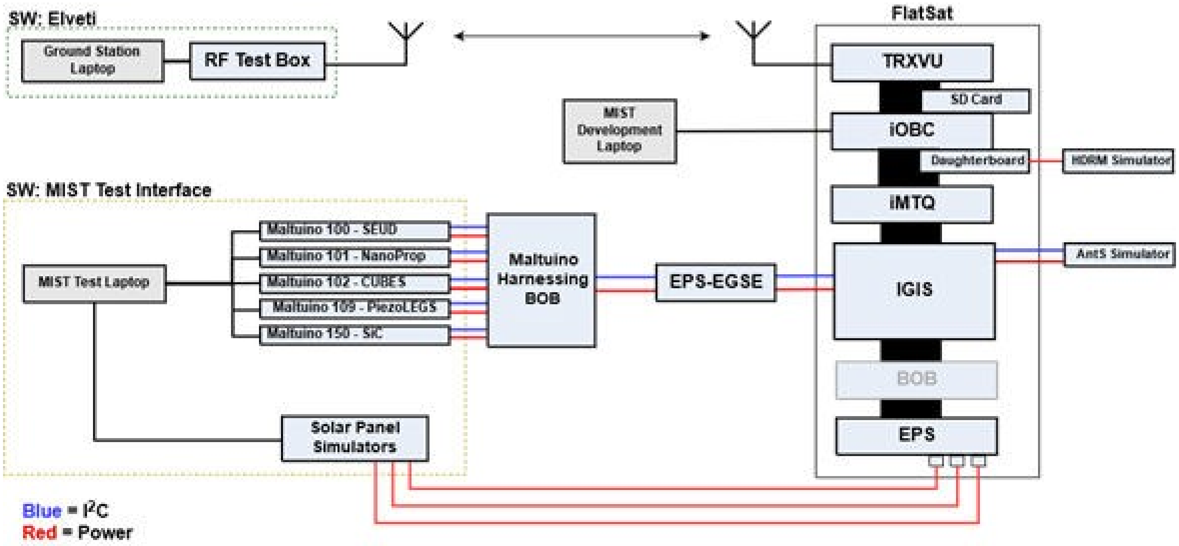


Figure 40 Block diagram of the power system flight simulation bench test model setup.

The TRXVU radio shown in Figure 40 will be used in future flight simulations, but not used for the power system simulations, and is to simple quarter-wave whip antennas to communicate with the RF Checkout Box that simulates the ground station.

The MIST Test Interface is a MATLAB based software used to manage the loads of the experiment simulators. It allows both the selection of a constant load and the set-up of a scheduled power profile. The software is provided with a GUI to allow an easier management of the test, and it is designed to be easy to use and compatible with different machines.

The purpose of the test was to:

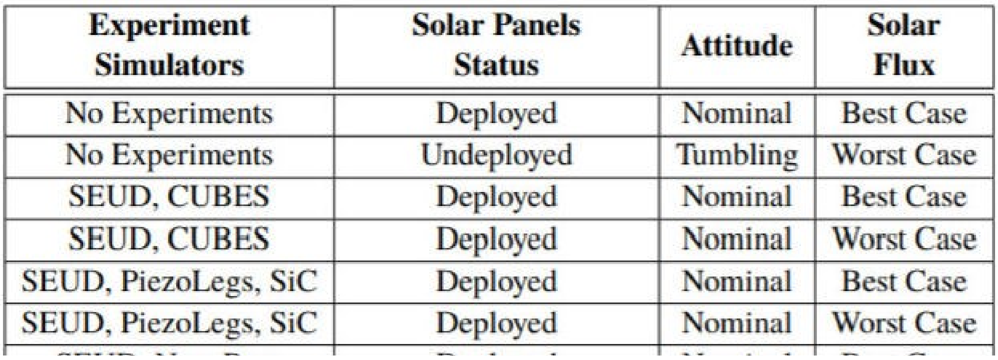
- Verify the power budget analysis
- Measure the DoD of the battery pack
- Check that the payload power demands do not interfere with the EPS functionalities.

To test these cases, the satellite needs to be tested on a system level, to understand the effect that different subsystems can have on each other. At the same time, control of every subsystem is required to separate eventual effects showing on the tests. The testing can be performed with the design of a test framework. The hardware component of this framework is a legacy of the project from previous student teams, and it can be divided into three separate systems:

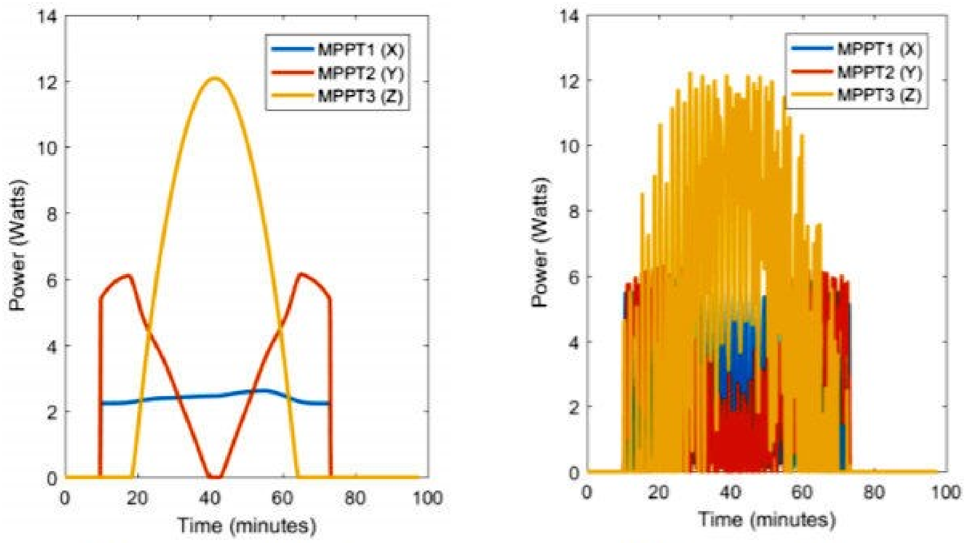
The SPS boards are controlled by a MATLAB software, [available on GITLAB], that allows both a manual control of the input power (for charging purposes) and an automated orbital simulation of the input power. The power profiles that the SPS can simulate are computed by the MATLAB software in several scenarios, and a combination thereof, such as:

- Nominal attitude or tumbling (5°/s),
- Deployed or un-deployed solar panels,
- High or low solar flux (winter and summer case).

Each of these cases can be modified according to the test case. Finally, the SPS can be calibrated to output the real power, taking into account the non-idealization of the solar panels used in MIST. Figure 41 shows the simulation cases run during this test and in Figure 42 the SPS output power in two extreme cases – best case solar flux, nominal attitude and worst case solar flux and tumbling attitude.



Experiment Simulators	Solar Panels Status	Attitude	Solar Flux
No Experiments	Deployed	Nominal	Best Case
No Experiments	Undeployed	Tumbling	Worst Case
SEUD, CUBES	Deployed	Nominal	Best Case
SEUD, CUBES	Deployed	Nominal	Worst Case
SEUD, PiezoLegs, SiC	Deployed	Nominal	Best Case
SEUD, PiezoLegs, SiC	Deployed	Nominal	Worst Case



(a) Best case, nominal attitude

(b) Worst case, tumbling

Figure 42 Input power in two extreme cases.

Figure 43 Shows the battery voltage during a simulation with SEUD and CUBES turned on continuously during the “worst case” solar flux.

This graph shows that the battery voltage drops each orbit and the state-of-charge falls during the day in good agreement with the numerical simulation in Figure 19.

In Figure 44 the “Flatsat” is at the back of the lab bench, the “Maltuinos” on the right of the aluminum mounting plate and the solar panel simulators on the left side of the aluminum plate. The “Maltuinos” are equipped with small fans to dissipate heat from the lead resistors on the back of the printed circuit boards.

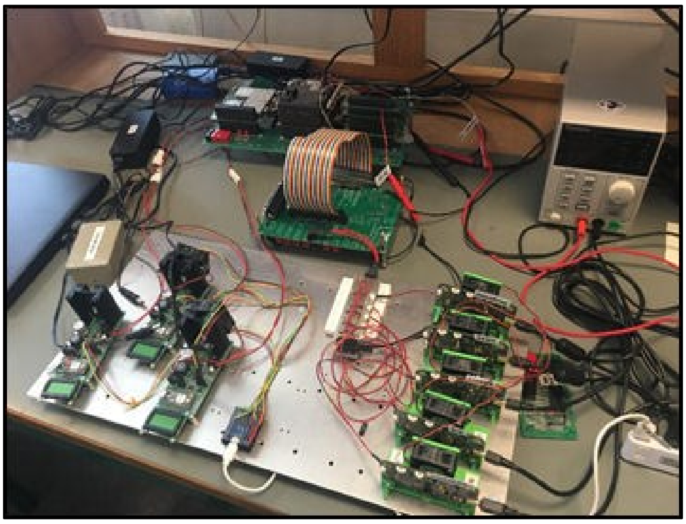


Figure 44 Power system flight sim setup.

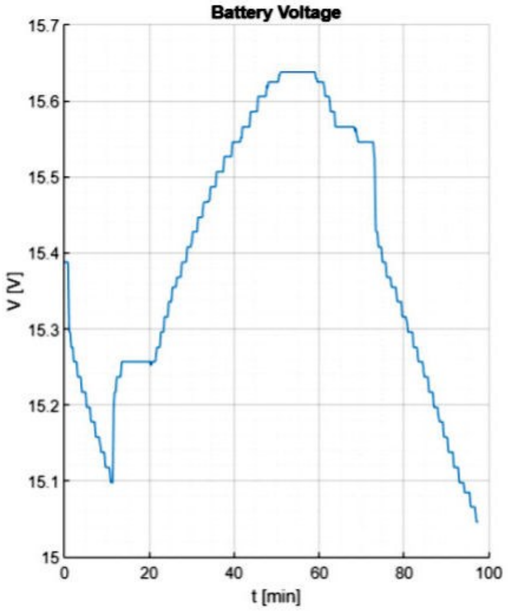


Figure 43 Battery voltage during one orbit in "worst case" solar flux with SEUD and CUBES on continuously.

4.3 Development Status Overview

Subsystem/ element	**Manufacturer**	**Model**	**Status**
CUBES	In-house KTH	EM	Manufactured and tested.
		Prototype 1	Flown on stratospheric balloon Aug 2019
		Prototype 2	To be manufactured and tested fall 2019
		FM	Expected delivery January 2020
LEGS	COTS (Piezomotor)	EM	Tested together with M177 SiC
		FM	Expected delivery January 2020
Nanoprop	COTS (Gomspace)	FM	To be delivered Fall 2019. Acceptance tested.
SEUD SEUD w/ camera	In-house KTH	EM	Manufactured and tested.
		FM	Expected delivery January 2020
SiC	In-house KTH	EM	Manufactured and tested.
		FM	Expected delivery January 2020
Onboard computer	COTS (ISIS)	EM	Delivered 24 February 2016
-“ -	COTS (ISIS)	FM	Delivered 15 October 2016
Antenna (AntS)	COTS (ISIS)		Delivered 20 Dec 2016
Structure	COTS (ISIS)	FM	Delivered 18 March 2016
Power system (EPS)	COTS (Gomspace)	EM	Delivered 20 Dec 2016
-“ -	COTS (Gomspace)	FM	Delivered 16 April 2019
Battery (BP4)	COTS (Gomspace)	EM	Delivered 20 Dec 2016
Battery (BP4)	COTS (Gomspace)	FM	To be ordered closer to launch.
Magnetorquer	COTS (ISIS)	FM	Delivered 4 July 2016
TT&C (TRXVU)	COTS (ISIS)	FM	Delivered 20 February 2017
Generic Interface system	ISIS	FM	Delivered 27 May 2019
OBC daughter board	ISIS	FM	Delivered 27 May 2019
Solar panels	COTS (ISIS)	FM	Delivered 11 September 2019
Solar panel release mech	COTS (ISIS)	FM	Delivered 11 September 2019
Ground Segment H/W	Various	-	To be ordered
Mission Control S/W	Solenix	-	License obtained in 2017

A more detailed summary of the development status is given in the table below.

Subsystem/area	**Status**
Mechanical design	Frozen. MIST-specific ribs delivered from ISIS.
Harness	Frozen. Test harness installed on mock-up.
MIST-specific electrical units	Specified, designed and delivered. (Refers to IGIS, OBC DB)
Thermal control	An adequate design has been found.
Attitude control	Software delivered. Tests started.

Subsystem/area	Status
On-board software	Basic framework ready. Many S/W tasks need to be developed.
Functional testing	Planned in detail. Testing incl. flight sims have started.
Ground station	Overall design frozen. Infrastructure under definition. Procurement started in February 2020.
Thermal testing	Thermal balance test studied. Overall test plan in fall 2019.
Mechanical testing	Overall test plan to be developed in spring 2019.
Magnetic testing	Test plan to be developed in spring 2020.
Experiment development	Prototypes exist for all experiments. See section 4.3.

4.4 Facilities and Ground Support Equipment

- Final assembly of the satellite will be performed in a **clean air bench** (Level 5 according to ISO 14644) at the MIST integration lab.
- The **vibration tests** will be performed either at the KTH Space Technology Lab or at Innventia in Kista, a nearby suburb of Stockholm. The shock test can probably be made at KTH. A vibration adapter for a 3U Cubesat is available in-house at KTH.
- The **thermal tests** may include a combined thermal cycling test (in the table called thermal-vacuum) and a thermal balance test to check assumptions in the thermal model. The bake-out is something carried out near the launch. All thermal tests are planned to be performed at the KTH's thermal vacuum test chamber (Figure 45) at AlbaNova University Center near the MIST integration lab.
- A **magnetic survey** of MIST is needed. The requirements for this test will be explored during the fall 2019 by using our engineering support contract with ISIS and by consulting the corresponding work done in the SEAM Cubesat project.

Figure 45 The MIST EM with 3D-printed experiments in the KTH vacuum test chamber at its inauguration, spring 2019.

4.5 CubeSat Testing

Action	[Y/N]	Describe **what**, **how** and to **what level**
Recharging during testing	N	
Switching on/ off during testing (also inside the thermal vacuum chamber)	N	
Send and receive telecommands to/ from your CubeSat (also inside the thermal vacuum chamber).	Y	Telecommands to run at least one of the experiments (CUBES) will be sent to the satellite via the umbilical.
Test sensors installed	Y	The CubeSat will have TBD thermocouples installed, which will be cut after the TVAC testing
Software updates are possible on-ground/ in orbit after testing	Y	Software updates are possible on-ground, not in orbit.
Accessibility to the internal part of the satellite for executing repairs or change components	Y	Solar panels need to be removed to provide access
Screws and nuts secured inside/ outside the CubeSat		TBD

5 PROJECT ORGANISATION

5.1 Organigram

The team leader and system engineer, Mr Sven Grahn, works full time on MIST and reports to the KTH Space Centre director, Professor Christer Fuglesang, the endorsing professor for MIST.

Mr Grahn, b. 1946, has a M.Sc. in Engineering Physics from KTH and is an Honorary Doctor at KTH. Until his retirement he served 31 years at the Swedish Space Corporation where he was the project manager of the first satellite entirely built in Sweden, the plasma physics satellite Freja, successfully launched in 1992. Mr Grahn then served as the general manager of SSC's space systems division that developed such spacecraft as the Odin orbital observatory (still operating after 19 years) and ESA's SMART-1 Moon probe.

Two more employed persons devote a substantial (25-50%) part of the working week to MIST – the project teaching assistant (Ms Agnes Gårdeback, engineering physics student) and Mr Theodor-Adrian Stana (lead electronics engineer in the Astroparticle physics group and designer of the Cubes experiment).

Students work in sub-teams concentrating on certain subjects. Each sub-team has a supervisor as set out in the table below. Please note that teaching assistants are paid "by the hour" for their supervision effort.

Sub-team	Supervisor name	Position
Mech. & system budgets	Agnes Gårdebäck	Teaching assistant
Thermal team	Sven Grahn	Team leader
Ground station team	Sven Grahn	Team leader
Electrical team	Theodor-Adrian Stana	Lead Electronics Engineer, Physics Dept.
OBC S/W team	Main: David Broman Assisting: Saranya Natarajan John Wikman Andrii Berezovskyi Elias Joahnsson William Stackenäs	Assoc. Professor, Software eng. PHD student, Embedded Syst Teaching assistant PHD student, Mechatronics Teaching assistant Teaching assistant
ADCS S/W	Federico Raiti	Graduated student, Teaching assistant.
B.Sc. thesis	Linda Eliasson	PhD student, Physics

Table 10 shows the national origin of students. Students from the rest of the EU make up 22 of the total, so India is the third most common national origin of the students.
Some students in Aerospace Engineering have taken courses related to the Electrical Engineering School. In general, the aerospace students mostly take the "Space" track in their master's degree.

Origin	Number
Sweden	51
Other EU countries	28
India	16
Asia, other	6
Middle East	4
Mexico	2
Total	**107**

Table 10 National origin of students.

Students perform their work in MIST under the auspices of project courses with titles such as "Project course in Aerospace Engineering" or "Embedded systems design project". Students can earn up to 15 credits. 15 credits can be earned in one or two semesters, while the lower number of credits (such as 7.5 or 9 credits) are earned in one semester.

The vast majority of students working in the project for project course credits have been fourth and fifth year students. A few second and third year students have earned course credits in MIST. Of course those students doing the B.Sc. thesis work in MIST earn credits, but these are not project course credits.

During the first seven semesters of the project students were recruited to stay one semester with the project. Some volunteered without getting credits one semester and then continued the next with credits. A few students worked for course credits one semester and then worked on their master's thesis within the project. But, in general, students stayed only one semester. This gradually turned out to be a major problem because the lack of continuity and the difficulty of transferring knowledge between students.

As will be discussed later, as the project became more mature, the level of detail and complexity of the student tasks increased considerably and it became necessary to switch to a system in which a two-semester effort was expected from the students.

As mentioned above the students are organized in sub-teams with their own supervisors.

Sub-team	**Present outline task assignments**	**# of students fall 2019**
System engineering	System budgets	1
Mechanical team	CAD, mass properties, mechanical tests	1
Thermal Team	Thermal simulation, test planning	2
ADCS team	Verification of the attitude control performance	2
OBC SW Team	Development of the on-board software	5
Ground Station team	Design and planning of the ground station	3
Electrical team	Functional testing incl. flight simulations	3

Students are/have been typically involved in the following analysis/design work:

- Power, data and link budgets.
- Mission analysis tasks such as lifetime estimates and ground station visibility.
- Mechanical accommodation of experiments.
- Cable harness design.
- Thermal design and analysis.
- Attitude control simulations including sensitivity to the magnetic dipole moment of the satellite and the effect of the Earth's albedo radiation on the control performance.
- Functional testing and flight simulations with real hardware.
- Development of flight simulation tools such as experiment simulators (data and power drain), on-board computer simulator, solar panel simulator.
- Design of the ground station including selection of subsystems and interfaces with the building.
- On-board software including the MIST Space protocol, an on-board communications protocol.
- Adaptation of the procured mission control software to the MIST mission.
- Planning and execution of environmental tests.

The project office and integration laboratory is located in the premises of the Space and Plasma Physics Group at Teknikringen 31.

5.2 Project Planning

Semester	**Major planned events, and goals for the end of each semester**
Spring 2020	Ground station design ready, procurement started. Cable harness manufactured. Planning of the mechanical testing of the satellite completed. Planning of the thermal testing of the satellite. Onboard software ready enough to be installed in flight computer for initial tests. Frequency permit request submitted. Attitude control software tested with ”software-in-the-loop” method.
Fall 2020	Installation of ground station antenna on the roof of Teknikringen 29. Ground station indoor equipment installed. On-board software review Full scale flight simulations with complete onboard software. Attitude control software tested with ”hardware-in-the-loop” method. Compatibility tests with the ground station. All experiments flight units delivered.
2021	Integration Readiness Review. Satellite integrated with all flight units for the first time. Mechanical tests started. Thermal testing. Earliest possible launch of MIST. Preceded by • Flight Readiness Review Verify ready for shipping to launch site) • Launch Readiness Review

Phase	**Started**		**Concluded**		**Comments**
	[Y/N]	**Date (mm/yy)**	**[Y/N]**	**Date (mm/yy)**	
Mission analysis/ need identification	*Y*	*10/14*	*Y*	12/15	Experiments defined.
Concept definition / Feasibility study	*Y*	*02/15*	*Y*	*12/15*	Subsystems specified/procured
Preliminary design phase	*Y*	*01/16*	*Y*	12/16	3D printed mock-up finished
Detailed design	*Y*	*01/17*	*Y*	06/19	Re-design 2019, 2 exp. deleted
Thermal model / analysis performed	*Y*	*01/15*	*Y*	06/19	New analysis after re-design
Structural model	*Y*	*01/15*	*Y*	06/19	New CAD design after re-design
Attitude control analysis	Y	01/16	Y	06/18	Three MSc theses
• OBC EM • Structure • MGSE • Magnetorquer/magnetometer • OBC FM	*Y*	*02/16*	*Y*	09/19	Only minor harness items left to deliver

Phase	Started		Concluded		Comments
	[Y/N]	Date (mm/yy)	[Y/N]	Date (mm/yy)	
• EPS • Battery • Antenna system • TT&C • EGSE • Interface circuit board (IGIS) • OBC Daughter board • Solar panels • Hold-down & Release Mech.					
Subsystems tested so far: • Magnetorquer/magnetometer • OBC FM • EPS • Battery • TT&C • EGSE	Y	01/17	N		Antenna system deployment will not be tested. Listed subsystems tested on Flatsat flight simulation.
Experiment simulators	Y	12/17	N		Exp. simulators on Arduinos tested with OBC EM.
SEUD experiment	Y	09/18	N		Comms test to MCS tested
Flatsat testing performed	Y	09/17	N		
CubeSat Integration on System level	N				
CubeSat fully integrated	N				
Ground station installed	N				
Functional testing	Y	09/17	N		
Flight ready	N				
Ground station operational	N				
Launch opportunity secured	N				

5.3 Outreach

The outreach activities in MIST were given substantial attention when the project started by displaying a mock-up of the satellite at the Science Museum in Stockholm and appearance s in Swedish media. After that initial outreach activity less attention has been given to outreach because the relative slow progress of the project.

However, outreach activities are continuously performed and more are planned for the period when the launch draws nearer and when the satellite is in orbit.

- MIST students regularly present the project at the bi-yearly conference among Swedish apace actors, the Space Forum and the twice-a-year public space evenet “KTH Space Rendez-vous”.
- The project is prominently displayed at a space technology exhibit that moves between KTH’s campuses.
- Students also present the project at selected Cubesat conferences in Europe.
- www.mistsatellite.space is used chiefly to communicate activities in the project to KTH students, the project’s sponsors, suppliers and as a recruitment tool for new students. It contains pictures and videos of recent events in the project.
- The projects thoroughly presented to the local space industry at half-day “end-of-semester-meetings” (EOSM) often attended by representatives of Swedish space industry (e.g. SSC, OHB Sweden, OmniSys, Gomspace).
- The camera on the satellite is included purely as an “outreach” feature. The plan is to produce “the picture” of the month for public release during the first year in orbit. The camera is designed so that its field of view covers the major population centres of Sweden in one picture.
- The project has a long-standing agreement with the Science Museum in Stockholm to promote the project using the resources of the museum once the satellite comes closer to launch. Our endorsing professor, former ESA astronaut Fuglesang, is the chairman of the board of the Science Museum.

5.4 Main Challenges to the Project

- The project scope at its initiation was very ambitious and there were initially eight experiments planned. This created many problems, especially in technical coordination work and thermal design which suffered from contradicting requirements.
- To keep a lean budget it was decided to procure subsystems piece-by-piece and not as a complete system. MIST became a small customer at the subsystem supplier which gave the project lower priority in the production and resulting delays. The project still suffers from these delays.
- The decision was taken at an early stage to let students design one subsystem, the on-board software. It turned out to be difficult to find students to work on this subsystem, partly caused by the academic structure of KTH. This has caused delays.
- At the moment there is enough funding to complete the satellite, but funding is lacking for the launch and possibly also for part of the establishment costs for the ground station.
- The professional (research engineer) and graduate student manpower for student team supervision and key technical work is subject to turnover and the fact that most of this staff works part-time on MIST.
- The schedule outlined in this document is “success-oriented” in that it depends very much on the effects of student and supervisor turnover. Any delays caused by such turnover effects lead to higher costs and creates a pressure on the budget. A vicious circle.

- The experiments developed in KTH are also subject to student turnover effects creating risks of delay.
- To alleviate the effects of student turnover it was decided to give priority to students that could stay with the project a whole year at a 25% engagement level. This works for 4th year students, but not for 5th year students.
- To somewhat compensate for the lack of supervisor resources technical support has been procured from the main subsystem supplier. This action has been helpful in solving problems where KTH's experience is limited.

6 ACADEMIC RETURN

- Most students that work in MIST come from the Space Track in the aerospace master's programme. Thus, most students in MIST have a good theoretical background in fundamentals of spaceflight, spacecraft dynamics, system integration and basic space science. The MIST project is a direct extension of the regular coursework in the Space Track and teachers from that track are used as advisors in MIST.
- The KTH Space Centre has developed the 3U Cubesat SEAM within an EU project. This was not a student project per se, but several PhD and MSc level students worked on the project.
- KTH has run several REXUS sounding rocket projects which are conducted in the same building as the MIST project.
- The experiments on MIST from KTH research groups are distinctly part of the research programs of these groups.
- The reason for seeking support from Fly Your Satellite for MIST is to
    - obtain additional technical resources for supervising students and solving technical problems that may appear.
    - obtain an opportunity to launch MIST.

APPENDIX A: TECHNICAL SPECIFICATION

The requirements for MIST listed below were developed during the need identification and feasibility phases during the period October 2014-December 2015.

Req ID	Requirement text
1	**Structure:** A 3U Cubesat conforming to CubeSat Design Specification Rev 13
2	**Experiment orientation:** Radiation experiments shall have access to open space in a direction away from the sun and a 2π sr field-of view. For the reference orbit this means in the –W direction. Any optical camera shall have access to the –Z face of the satellite normally pointing in the –U direction.
3	**Experiment accommodation.** The following experiment shall be fitted in the satellite: • Nanoprop – cold gas propulsion system from Gomspace. • SEUD- Single Event Upset Detector from KTH. • MOREBAC – biological experiment from KTH (later deleted) • RATEX-J – radiation experiment from Sw. Inst. Space Physics (later deleted). • SiC – silicon carbide electronics test from KTH. • LEGS- Piezoelectric motor from Piezomotor. • CUBES – X-ray detector test from KTH.
4	**Reference orbit:** For system design purposes the following orbital parameters shall be used: Sun-synchronous at h=643 km, LTDN in the range 0930-1045.
5	**Operational attitude**: The nominal orientation of the satellite shall be: the +Z spacecraft axis points along the + U axis in the orbital frame, the +X-axis along the +W axis and the +Y points along the -V axis. (See Figure 15 on page 26).
6	**Attitude performance** In sunlight: • The pointing *should* be determined within 5° of actual attitude. • The satellite *should* point within 15° of the desired attitude. This shall be achieved with a total magnetic dipole moment of the satellite less than or equal to 50 mAm^2 and demonstrated by pre-launch analysis.
7	**Commands:** Real time well time-tagged commands shall be supported.
8	**Data bus:** The I2C bus shall be used by all experiments.
9	**The TT&C system** shall use amateur band frequencies (UHF down, VHF up) and support full duplex operations.
10	**Ground station:** A single ground station located at 59.35° N, 18.07° E shall be able to support the mission.
11	**Mission operations:** Shall be planned based on a 9.6 kb/s gross downlink data rate.
12	**Materials requirements**: NASA-STD-6016 Std. materials & processes req. for S/C
13	**Mechanical test and bake out requirements:** NASA LSP-REQ-317.01
14	**Thermal vacuum cycling test requirements:** MIL-STD 1540 B, GSFC-STD-7000
15	**Procurement:** subsystems shall be COTS except the on-board software left to students.