SSC09-XII-9

Lessons Learned from the First Swiss Pico-Satellite: SwissCube

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ABSTRACT

SwissCube is the first pico-satellite developed by the Space Center at the Federal Institute of Technology of Lausanne (EPFL) in partnership with the University of Neuchatel and five engineering schools (HES-SO, FHNW) in Switzerland. SwissCube will be launch on PSLV in summer 2009. The educational objective of the project is to provide a hands-on experience of the whole development cycles of satellites, and in parallel enhance flexibility, work autonomy and communication skills in a team composed of about 15 laboratories. SwissCube primary science objective is to measure the intensity of the airglow, a thin luminescence layer in the upper atmosphere that emits in near-infrared. For that purpose, a custom made telescope with a CMOS detector was designed. The concept for a low-cost Earth-sensor will also be validated with this telescope. The project built three models (Engineering Qualification Model, Flight Model, and Flight Spare) and extensively tested the EQM. This paper will present the project organization, mission, and satellite description. It will outline the capabilities and performance of the satellite as characterized during the test campaign. Technical as well as programmatic lessons learned will be addressed. Flight results will also be discussed if available.

INTRODUCTION

SwissCube will be launched from the Indian launch base SHAR on the C-14 mission of the PSLV rocket, most probably over the summer 09. This launch, as well as the 4-month mission operations will validate a 3-year effort of the SwissCube development. SwissCube is a pico-satellite of the CubeSat standard. Besides the educational objectives, which have already been fulfilled, SwissCube will capture intensity information about the Airglow emission on top of our atmosphere. This paper summarizes this great adventure for EPFL and its 5 academic partners. It will provide the main features of the project organization, quite uncommon for CubeSats. It will then relate to the mission and scientific/technology objectives. After a short overview, each main subsystem will be briefly described and the lessons learned will be presented, such that future CubeSat developers can benefit from the solutions chosen on SwissCube.

PROJECT ORGANISATION

The SwissCube project was originally planned over 2.5 years and effectively ran over 3 years. Figure 1 shows the actual schedule, from Phase A to Phase D, launch being delayed for several months.

About 15 laboratories from EPFL, the University of Neuchatel, and 5 engineering schools (HEIG-VD, HE-ARC, HEVS, HE-FR and FHNW), spread over all Switzerland participated in the design, analysis, subsystem breadboards, and tests of the subsystems. Each laboratory provided analysis, software elements or hardware assemblies (boards) to the puzzle. A laboratory professor or assistant was thus assigned to supervise semester (4 months, 1 day/week) or master projects (4 months full time) and provide the technical expertise needed at the element or subsystem level. This professor or assistant ensured continuity between the students working under his/her laboratory. About 180 students participated in the project over 3 years.

To provide consistency in the design, interface definition and testing at the system level, a systems engineering team was quickly assembled after the first year (at the beginning of Phase B). This team included 3 then 4 students finishing their studies and hired by the Space Center EPFL, part of a 1 PhD's time (20%) and about 5 master level students (typically 20% time). This team ensured communication with the laboratories about all system related technical matters (ICD, reviews…). It also prepared and performed the Phase D work, meaning the fabrication, assembly and integration tests of the qualification and flight model, as well as the qualification and acceptance tests themselves.

The test model philosophy adopted includes in Phase C and D an Integration Model (IM), a Structural and Thermal Model (STM), an Engineering Qualification Model (EQM), a Flight Model (FM), and a Flight Spare (FS). This philosophy has been the one most appropriate for the organization specific to this project. The flight spare was fabricated but was not assembled during Phase D.

The cost of the satellite and ground station hardware, administrative expenses, tests, operations and launch are around 400 k€, including students' salaries over the summers.

Lessons learned

Although communication glitches always happen in a multi-site project, the work structure adopted turned out to be efficient. Communication was facilitated by the fact that systems engineers in each main discipline would interface with the laboratories on a weekly basis.

Furthermore, the decision power resided in the systems engineering team who had all the elements in hand. A last minute change in the software architecture was in fact possible thanks to the flexibility of this organization.

Scheduling end-of-phase reviews was of outmost importance for the project. Reviewers from the Swiss space industry, from other CubeSat teams, from the Radio-Amateur community and from the European Space Agency attended the reviews and provided comments. Not only did the project get extremely valuable advices from the reviewers, but it also forced the team to converge on design solutions and take system level decisions.

Fabrication, assembly and testing of 2 models took longer than expected. Due to schedule constraints, the Flight Model had to be assembled simultaneously with the qualification testing of the EQM, putting the team under great stress and fatigue. A few more months in the planning for sequential fabrication and testing would have been beneficial. Thus the planning for fabrication and test should not be overlooked. Tests preparation also demands a significant amount of time. Our test set-up required the development of extra electronics, mechanical pieces and software. Preparing good test procedures also saved time during the tests.

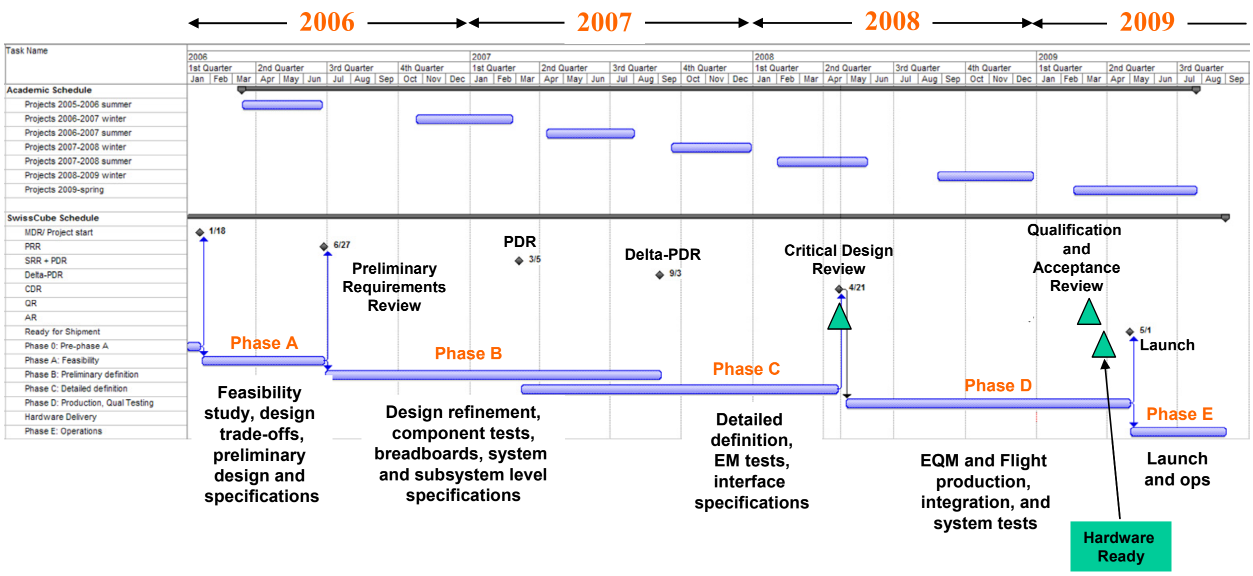

Figure 1: SwissCube 3-year development schedule (launch was delayed)

MISSION DESCRIPTION

Although the satellite has been designed for altitudes between 400 km and 1000 km, SwissCube will effectively be launched on a 720 km sunsynchronous orbit, 98^{o} inclination, 12h at descending node. The satellite will be released from a Single Pod Deployer (SPL), provided by Astro und Feinwerkwechnik AG in Germany (as seen in Figure 2).

Figure 2: SwissCube FM in its SPL deployer

On this orbit, the eclipse times are about 35 min duration and the orbital period is 99 min. Mean access times with the ground station between 5 and 10 minutes are expected. This orbit will have the only drawback of constraining the airglow observations to very illuminated areas during the day.

The satellite will be listened to and commanded from the EPFL and HES-Fribourg ground stations about once a day, but its beacon will be emitting constantly with basic but useful information about the health of the satellite. Right after release from the PPOD, the 4 separation switches (redundant) will activate the on-board power system. Fifteen minutes later, the antennas will deploy and the beacon message will be sent. The satellite will then wait for an uplink command once the satellite has been located. The first few weeks (up to 4) will see the commissioning of the satellite, with verification of each subsystem and performance characterization and calibration of sensors. After commissioning, the science phase will start with day and night observations. Downlinks are planned at every opportunity during daytime.

SCIENCE OBJECTIVES AND PAYLOAD[1]

Besides the educational objectives, the SwissCube mission objective is to observe the airglow phenomenon (intensity) over selected latitudes and longitudes for a period of 4 months (possibly up to 1 year). The airglow is a photoluminescence of the atmosphere (more obviously seen at night and known as the nightglow) occurring at approximately 100 km altitude (see Figure 3). It is principally due to the recombination of the diatomic oxygen molecule, which is dissociated during the day. The motivation for these observations is to demonstrate that the airglow emissions are strong enough to be measured by an off-the-shelf detector, thus validating the concept for a low-cost Earth sensor.

A model of the airglow emissions has been elaborated and flight measurements will validate or bring additional information about airglow dependence on latitude, altitude and local solar time.

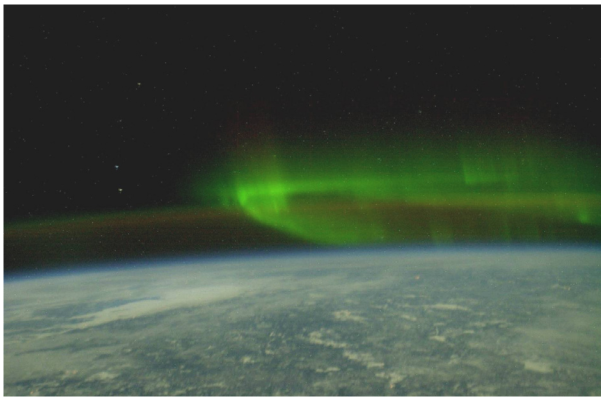

Figure 3: Atmospheric airglow (light green band) and aurora

The payload consists of a telescope which takes images of the airglow emissions. The telescope has a length of 45 mm (see Figure 4). At one end, a CMOS detector captures images with a resolution of 188 x 120 pixels and a pixel size of 24 µm via a focusing optics, which provides a field of view (FOV) of 18.8° x 29.4° and a resolution of 0.16°/pixel. A bandpass filter centered at 767 nm, with a bandwidth of 20 nm, selects the desired wavelength of the airglow.

A triplet design consisting of standard lenses only has been chosen due to reduced cost and complexity of the optics. Its RMS spot diagram satisfies the targeted resolution for a pixel pitch of 24 µm for 95% of the rays. An analysis on the spot diagram in function of the position of the lenses and the detector showed that the performance of the optical system highly depends on the distance between the sensor plane and the last lens. Thus, the mechanical design of the payload has been improved to allow positioning the detector in the most optimal way during the payload assembly by using spacers.

At the front end of the payload, a baffle protects the optical system and the detector from straylight. The payload is commanded by the ground to take images and sends back down about one image per week.

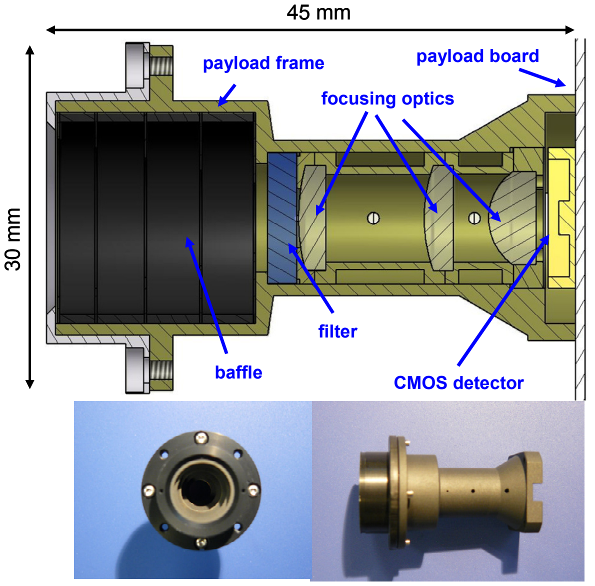

Figure 4: SwissCube Payload description

The electronic circuit of the payload is attached to the optical system and bears the detector and the components required to successfully operate the detector and communicate with the I2C bus. It includes a microcontroller (MSP430F1611), a CMOS detector (MT9V032), used to capture images of the airglow emissions, a SRAM (R1LV0416CSB-7LI), used to speed up the read-out of the detector and store the image data until transfer to the ground via I2C, an oscillator (8 MHz HC-49/US SMD) which generates the time reference for the CMOS detector, and a temperature sensor (LM94022).

Since the CMOS detector has an active format of 752 x 480 pixels with 8 bits/pixel, the size of one image (with a Binning of 4 x 4 pixels) is 22 kBytes. The science data will be transferred to the ground in packets of 207 bytes (corresponding to one image line with CCSDS format) via the I2C interface.

Tests description

Several tests were performed during Phase C to characterize the performances of the opto-mechanical design and detector. To verify that the optical design and performance requirements remained unchanged under environmental conditions, several alignment tests were performed before and after each qualification and acceptance environmental tests.

The alignment tests were performed with the transportable payload test bed at room temperature. The test bed included a laser source at 760 nm, a laser diode – doublet – ND filter assembly, an additional ND filter of 1.4, a beam collimator and beam expender and support for the SwissCube satellite with two degrees-of-freedom (one rotation and one translation). With this test bed, the laser spot diameter was measured as a function of the incident angle at 760 nm. The shape and intensity of the spot determined the angular resolution and the FOV of the payload. An example is provided in Figure 5.

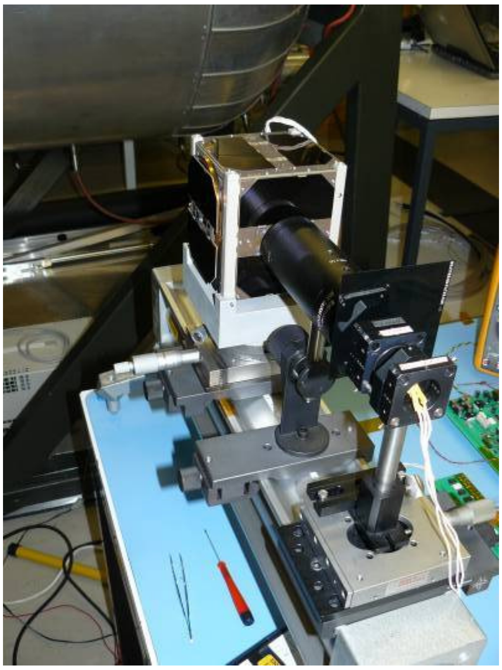

Figure 5: Alignment test set-up

Test results

Both the EQM and FM opto-mechanical system of the SwissCube payload successfully passed the vibration sine and random vibration tests, the pyro shock tests as well as the thermal vacuum cycling tests. Indeed, the spot measurements at different incident laser angles showed limited changes in position, shape and intensity distribution and the payload therefore satisfied the targeted resolution and field of view.

SATELLITE OVERVIEW

The philosophy in the development of SwissCube has been to implement functional redundancy in the critical systems, and a robust design but not redundant (to save mass and reduce complexity) to the systems necessary to satisfy the science mission objectives. This philosophy has driven architecture and design choices.

The mission critical functions were those which ensured launch survival and basic housekeeping data transmission. The non-critical functions included science payload operation and advanced housekeeping data transmission. Defining it as such clarified the ground for making architecture choices.

The implementation of the mission's critical functions is especially applicable to the Electrical Power System (EPS), Beacon Signal, fabrication processes and structural design to survive launch.

Basic reliability considerations start with EPS for which partial redundancy and robustness have been implemented to maximize reliability. Redundancy is achieved by having separate batteries, charge and discharge circuits and solar cells. Robustness is achieved by the simplicity of the system that does not require any programmable controller.

The downlink communication architecture relies on three different paths from simplest to most complex:

1) A basic hardware beacon residing on the EPS board generates a simple signal (callsign) which allows identifying the satellite from ground. This signal is then directed to the Beacon board where it is amplified and transmitted. This mode will be operated in case of an EPS microcontroller failure.

2) A more complex beacon signal message is generated by the EPS microcontroller (software). Again the signal is amplified and transmitted by the Beacon board. This signal can include status parameters of the satellite, such as bus voltages and temperatures. A hardware switch selects between both signals.

3) In case of a failure of the RF Beacon hardware, the signal can be sent via the COM board using the satellite's receiver and transmitter system.

However, the RF switch, used for downlink, still remains as single point of failure. By default this RF switch allows transmissions of the Beacon signal.

Mostly due to the project's organization, where responsibility of the development of each subsystem resided in laboratories spread over Switzerland, a distributed architecture was chosen for data processing. Thus each subsystem has its own board and own micro-controller (see Figure 6). This architecture is well adapted for fabrication and test of each subsystem independently. The COM, Payload, ADCS, and EPS subsystems all have a MSP430F1611 microcontroller, while the CDMS has an ATMEL ARM AT91M55800A OBC. However, since this microprocessor has no hardware I2C capability, it was decided that it would be linked by an SPI data bus to a MSP that would be used as an I2C-SPI bridge.

It is to be noted that at the last minute, software and hardware problems on the CDMS prevented its use at all. The CDMS is thus on-board the satellite but is cold. The software architecture was largely remodeled to accommodate this change without losing much of the capability of the satellite (this change did not affect the science objectives).

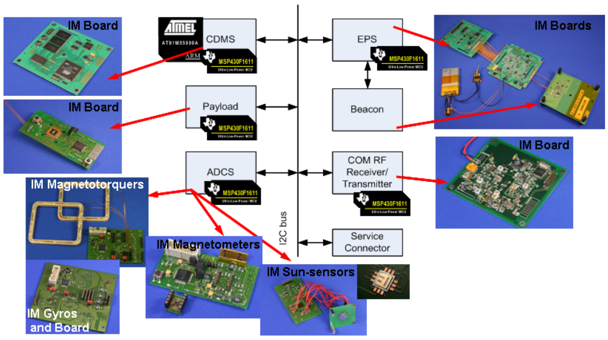

Figure 6: Data processing architecture

The overall accommodation of the subsystems is provided in Figure 7. The associated mass and energy budgets are given in Tables 1 and 2. All masses were weighted. As the total mass turned out much less than the 1 kg required, radiation shielding plates were added (included in the panels' masses). These plates are made of Aluminum and Tantalum (equivalent to 1 mm Al).

Table 1: SwissCube mass budget

Subsystem/Assembly	Mass [g]
EPS board	43.0
Battery box, batteries and control board	80.1
Motherboard	43.8
Connection Board	21.9
ADCS board + magnetotorquers	114.3
CDMS board	23.0
Payload module (PCB+mec)	38.5
COM board	33.0
BEACON board	17.3
Frame and secondary structure	139.5
Panel +X	23.3
Panel -X	23.5
Panel -Y (with antenna deploymnt system)	77.9
Panel +Y	45.1
Panel +Z	51.0
Panel -Z	48.2
Total	**823.4**

Table 2: Average energy budget per day (15 orbits)

Subsystem	Operating time	Energy [Wh]
Solar panels (approx 1.5W)	16h	+24.00
EPS-Motherboard	24h	-0.41
EPS-Power management board	24h	-1.34
COM RF => off RF => on	 24h 10min	 -3.41 -0.47
BEACON RF => off RF => on	 24h 5.6h	 -0.24 -2.27
ADCS (3 MT => on)	24h	-6.81
PAYLOAD	24h	-6.02
Margin		***+3.03***

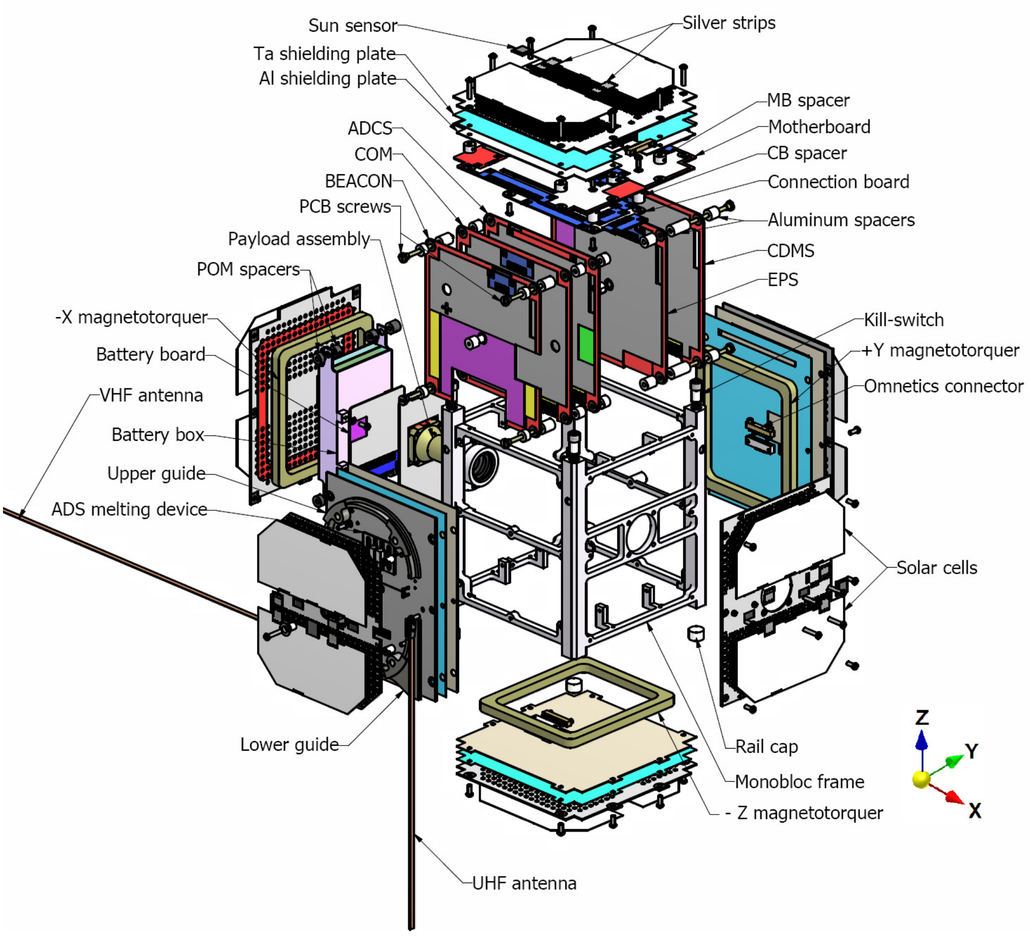

Figure 7: SwissCube exploded view of the subsystems

ENVIRONMENTAL REQUIREMENTS AND TESTS

A good system level test campaign was mandatory to ensure correct functioning of the satellite and validate its design. The EQM went through mechanical (sine, random, pyroshock), thermal (thermal vacuum cycling) EMC and RF compatibility testing at qualification levels. Although SwissCube was designed for a wide range of launch vehicles, the mechanical qualification followed the PSLV requirements with margin. For information, the random vibration requirements are provided in Table 3 for both qualification and acceptance.

Table 3: Random vibration tests at qualification and acceptance levels

Qualif.	Frequency [Hz]	20	110	250	1000	2000	**G_{rms}**
	PSD[10^{-3} g^2/Hz]	2	2	34	34	9	**6.7**
	Duration	2 min per axis					
Accept.	Frequency [Hz]	20	110	250	1000	2000	**G_{rms}**
	PSD[10^{-3} g^2/Hz]	1	1	15	15	4	**4.5**
	Duration	1 min per axis					

The thermal vacuum cycling (TVC) requirements are consistent with the ECSS standards and SwissCube requirements. They are summarized in Table 4.

Table 4: Thermal vacuum cycling tests at qualification and acceptance levels

	Qualification	**Acceptance**
# of cycles	8	4
Temp. MIN	- 55 °C	- 45 °C
Temp. MAX	+ 70 °C	+ 50 °C
Duration Tmin	45 min	35 min
Duration Tmax	70 min	60 min
Temperature rate (heating)	~ 2-4 °C/min (external) with sun simulator	
Temperature rate (cooling)	1 °C/min	
Pressure	< 10^{-5} Pa	
Stabilization criterion	1 °C/10 min	

The heating and cooling temperature rates represent the best slopes that could be achieved with the facilities and equipment. They are consistent with the ECSS requirements of temperature rate of change of < 20°C /min. The stabilization criterion of 1°C/10 min was not satisfied for the cold temperatures as it took several hours to reach them. Rather the plateau of cold temperatures would start as soon as Tmin was reached (see Figure 9 for 3 typical cycles).

The SwissCube FM was placed inside the thermal vacuum chamber on a rod attached to a rotation device (see Figure 8). The heating of the satellite was performed via two heating rings and a sun simulator. Cooling was passive via radiation to the shroud, which is continuously kept at -70°C. The rotation device on top of the chamber allowed for an almost 340 deg. rotation around the Z-axis of the satellite. After 340 deg., the satellite would turn in the opposite direction. The rotation velocity was about 1 deg/sec as expected in flight.

All functions of the satellite could be verified during the tests. Most of the performances of the subsystems could also be characterized either during the thermal characterization, or the TVC, or the battery characterization cycles.

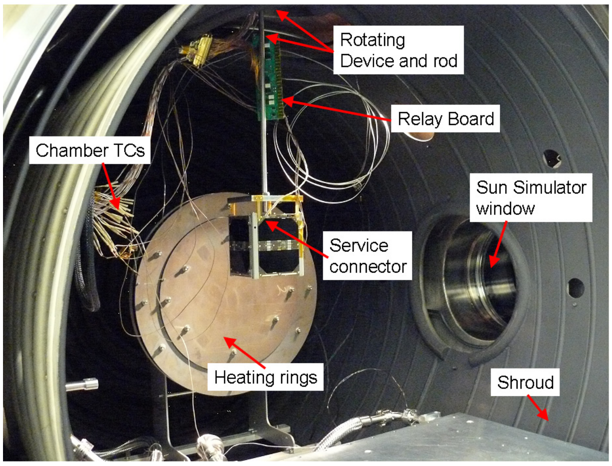

Figure 8: TVC test set-up

Lessons learned

One of the main results of the TVC test was to learn how to operate the satellite. Several resets were experienced and were related to the way the power demand is managed on the power bus. This was especially true for cold temperatures where the batteries were discharged. This behavior was corrected by respecting better the flight operational scenarios, where telecommunication is done with fully charged batteries. The ramp-up time for the telecom Power Amplifier (PA) was also changed to accommodate a few steps in current. These changes made a significant difference on the functional behavior of the satellite. Having a second opportunity to performance tests (first during qualification, second during acceptance) allowed to characterize performances better and to operate the satellite in a more efficient way the second time around. The team recognizes the benefit of having two models and series of tests.

On another note, for both qualification and acceptance, the test equipment failed many times during the test, always leaving the uncertainty that it could be a satellite failure. One of the reasons for this happening was that the test equipment was designed and fabricated in a very short time, and poorly tested. More attention should be brought to these aspects early on in the project. Also, cheap solutions for PCs or sun simulator are OK for non-critical tests but not for critical tests such as qualification or acceptance. More careful evaluation of the reliability of the ground test equipment should be done in the future.

About half of the problems encountered during qualification were related to test equipment problems, the other half to the satellite. On a satellite hardware level, the most frequent problem was reliability of capacitors. Both for qualification and acceptance, the most critical problem turned out to be failures of capacitors (capacitor manufacture defaults or under sizing). Careful evaluation of the problem and additional tests were performed to ensure a reliable resolution. However, one should keep in mind that the components used at off-the-shelf components not necessarily designed to operate under the stringent conditions of a qualification campaign. These sorts of problems, even though designed for, can be expected.

Another lesson learned was the management of the people during tests. As test campaigns are demanding (limited amount a time in a test facility), staffing for the TVC test quickly became an issue. Thus resources were called from less experienced students/team members. Although instructions would be provided, decision taking or resolution of problems would be a more difficult process. We do recommend as much as possible to keep the involvement of the key people during the stressful test campaigns.

And finally, although it was easy to accommodate tests to characterize at best the EPS, COM and PL subsystems, the assessment of the ADCS performances turned out to be a difficult task. A special test bench should have been set-up and will be in the future to address the ADCS needs.

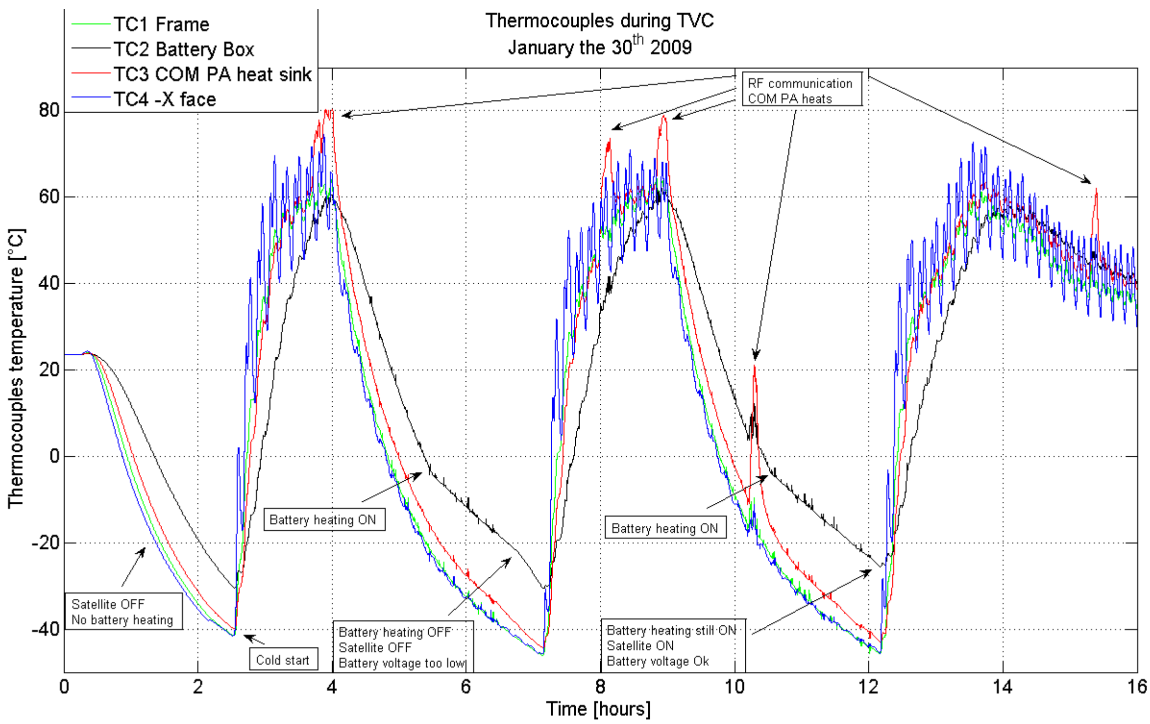

Figure 9: Acceptance first 3 TVC cycles

ELECTRICAL POWER SYSTEM

Because of the very small space available and the restricted budget, designing a reliable high efficiency electrical power system for a pico-satellite is a real challenge. At first, the power system architecture main-lines have been inspired from a design proposed by Dan Olsson at ESTEC for a micro-satellite.[2] Then the concept has been adapted for CubeSat. The architecture has been essentially driven by the following principles:

- Provide a *low voltage regulated* DC bus
- Control the bus voltage with an *analog* circuitry
- Be able to deploy antennas and emit a beacon message *without using a microcontroller*
- *Minimize* the power loss usually associated to voltage levels conversion and protections
- Try to keep a high reliability even when using *COTS components* (hard selection, redundancy)
- Take advantage of *very low consumption devices* to reach the sum of functionalities required by the mission.

By following these decisive factors the system resulted in a clear architecture. Basically, the electrical power system (EPS) is spread over 9 various electronic boards: the *6 faces* of the satellite where solar cells and protection diodes are soldered; the *motherboard* (analog circuitry) in charge of the DC bus control, batteries and solar cells management; the *battery board* in charge of the batteries locking and heating; the *power management board* (digital circuitry) in charge of the power distribution over all other subsystems, the start-up sequence management, the voltage and current measurements and the beacon message generation.

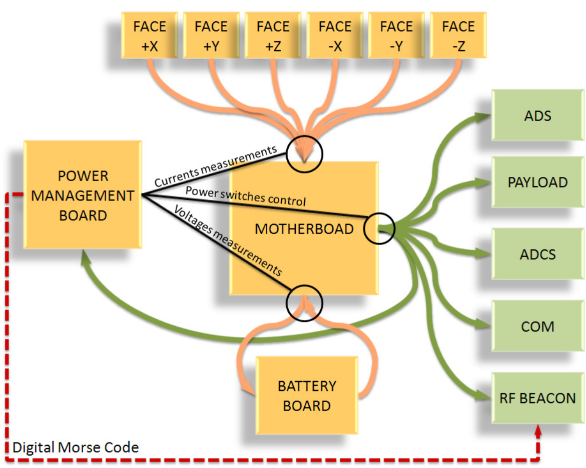

Figure 10: Simplified block diagram of power supply

Power generation

The satellites small size and power needs require the use of the most efficient solar cells on the market. GaAs based solar cells have the potential to reach very high efficiencies. The triple junction Solar cell assemblies (SCA's) used on SwissCube have a maximum efficiency of 25% (100µm coverglass included). They are soldered on printed circuit boards by using a process of screen printing developed at the Space Center of EPFL.[3] The average power generated by the satellite during the daylight period of its polar orbit is approx 1.5W.

Power storage

Two 1.2 ampere-hour lithium-Ion Polymer batteries from VARTA are used for the mission.[4] Their major advantage is a high energy density. So far bulging has been a major issue with Li-Poly but recent tests at ESA have shown that similar batteries than the ones selected, do not suffer from this problem.[5,6] Furthermore, they are radiation tolerant and conserve their charge under vacuum conditions.

The chosen depth of discharge (DOD) for the system is approximately 30% if both batteries are operational and 60% in the case of one operational unit. The low DOD has been chosen to increase life expectancy of the battery.

DC Bus control

The solar cells work on a fixed point of their I-V curve. As shown on Figure 11, measurements on solar cells show that the maximum power point (MPP) moves quickly to the left on the I-V curve when the sun begins to irradiate the solar panels (temperature increases). The MPP is then really close to the fixed working point which has been chosen for a worst case temperature of 75°C. As shown on the same graph, the voltage of this point is around 2V for one cell.

Taking in account the voltage drop of the wires, connector and the schottky protection diode, one panel with two cells in series at 75°C has a fixed voltage very close to 3.3V. This is the reason why the voltage of the power bus has been set at this value. At this working point, the efficiency of the panels should be around 18.5%.

This fixed-point concept has the advantage of being able to transmit the energy from the solar cells directly to the users (see Figure 12). Therefore the power losses due to a missing MPPT can be kept low.

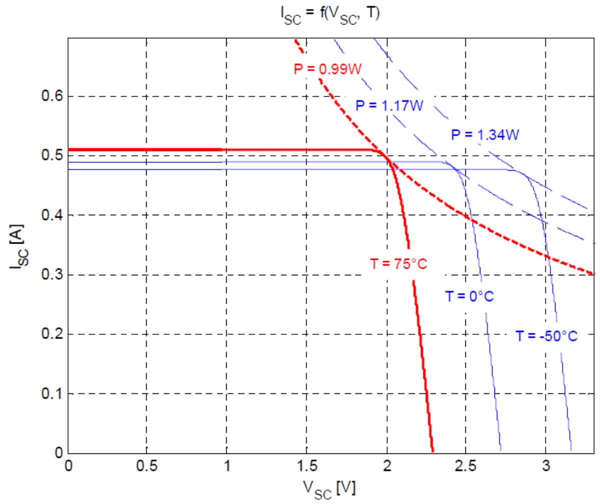

Figure 11: I-V curves as a function of the temperature (G=1350W/m2)

The voltage control of the bus is performed by an analog circuit. This circuit measures the voltage variations on the capacitors of the bus and instantly corrects it by charging or discharging the batteries. Thus, the control of the power injected in the capacitors results in a voltage accuracy of 3.3V ± 7%. When batteries are fully charged it is necessary to use a dissipation system in order to remain in control of the bus voltage.

Considering the reliability, the major advantage is that the system does not need any microcontroller to operate. Further charge and discharge circuits are redundant, i.e. the loss of one battery will not cause a mission critical failure.

Power budget

During the flight model integration, the average consumption of each subsystem was measured and reported in the Table 5.

During the thermal vacuum cycling of the flight model a sun simulator was used to heat up the satellite and simulate the sun light with approximately 1 solar constant. By rotating the satellite in front of the sun simulator the space conditions were better simulated. When the satellite faces were oriented perpendicularly to sun rays, the power generated by some of the panels was measured by the satellite itself. The results are provided in Table 6.

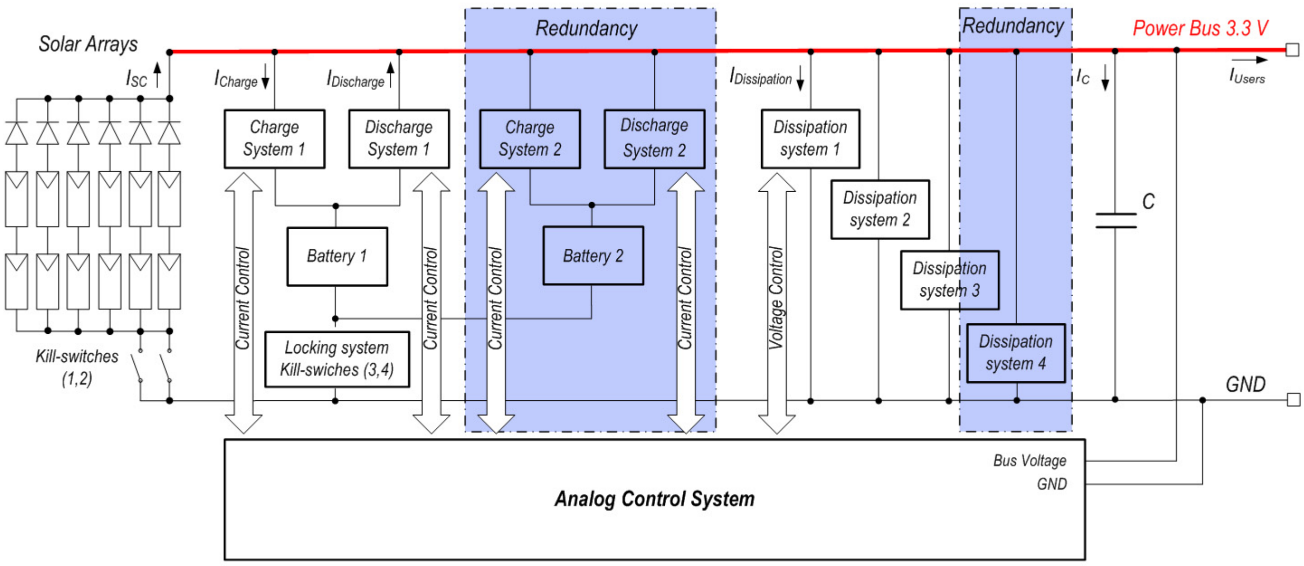

Figure 12: Power Bus voltage is controlled by charging and discharging the batteries

Table 5: Measured average power consumption

Subsystems	Average supply current	Average power	Comments
EPS-Motherboard	5 mA	17 mW	-
EPS-Power management board	15 mA	56 mW	-
COM	43 mA 890 mA	142 mW 2.94 W	RF => off RF => on
BEACON	3 mA 126 mA	10 mW 416 mW	RF => off RF => on
ADCS	41 mA	135 mW	No MT* (max15 mA each)
PAYLOAD	76 mA	251 mW	-

*MT: magnetotorquers

Table 6: Measured average power consumption

Housekeeping	Face +X	Face -X	Face +Y	Face -Y
Ave. current	272mA	309mA	311mA	324mA
Ave. power	1.01W	1.14W	1.15W	1.2W
Aver. power efficiency	12%	14%	14%	15%

These values are lower than excepted. One possible reason is the low precision of the sun simulator which gave probably less than one solar constant. Nevertheless, an average efficiency of 14% has been considered to calculate the power budget.

For a typical mission day with all subsystems activated and considering an albedo of 30% it is planned to perform 1 communication of 10 minutes per day. The energy budget is summarized in Table 2. It shows how the power is allocated during one day.

Power distribution

The power is distributed to the subsystems using appropriate switches. These switches are controlled by a logic enable coming from the microcontroller of the power management board. When the output load exceeds the current-limit threshold, or short-circuit is present, the power switch limits the output current to a safe level by switching into a constant-current mode, pulling an over current logic output low. This logic output is read by the microcontroller in order to react by switching off the subsystem affected.

Grounding and EMC design

As usually recommended for the power distribution interface grounding, the SwissCube has a single point "star" ground as show on Figure 13. The electrical ground is connected to the mechanical structure in a single point through a fault isolation resistance. This grounding configuration is very effective in reducing current loops formation into the 0V reference of the satellite.

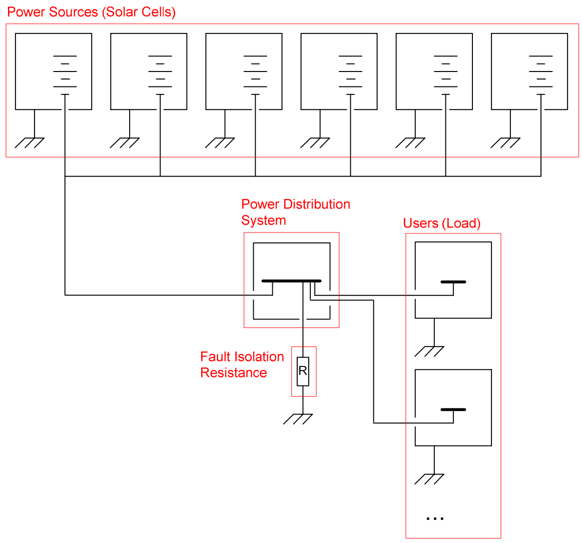

Figure 13: Power distribution interface grounding

It can be noted that all mechanical parts of the satellite have been connected to the frame in order to avoid electrostatic discharges.

Power and digital long wires are twisted in order to reduce the intensity of the emitted perturbations. The sensitivity of the analog signals wires to electromagnetic perturbations is also reduced by twisting them (see Figure 14).

Electrical tests

Several tests on the EPS have been performed during the design phase such as

- Charge and discharge current steps of 1 Amp on the power bus,
- Thermal verification of the dissipation system under vacuum,
- Battery heating tests under vacuum,
- Radiations tests at ESTEC (cumulated dose simulated with gamma rays at 1 MeV),
- Electromagnetic compatibility (EMC) tests
- Vibration tests.

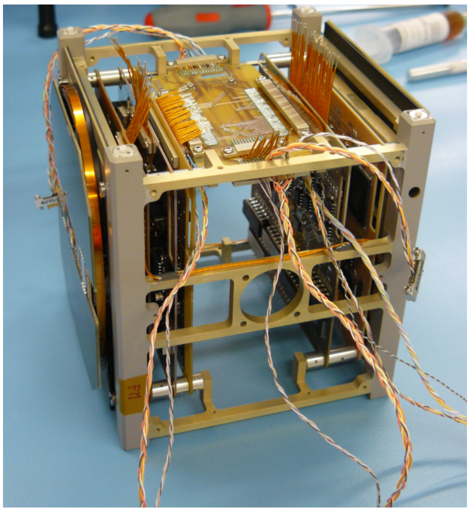

Figure 14: Long wires are twisted

All functionalities of the power system have been tested in the required temperature range in order to validate the robustness of the system. The overall satellite also underwent qualification and acceptance test campaigns.

Test results

Among all the results obtained during tests, some are more interesting than other, especially the radiation tests results performed at ESTEC. The total dose that SwissCube shall survive has been approximated at 20 krad[si]. As shown in the Table 7, some interesting aging effects appeared on EPS power management board after more than 20 krad[Si].

EMC tests were helpful too. They were firstly performed in the close field of the satellite with appropriate probes and spectrum analyser. The tests results were taken in account especially in reducing high frequency perturbations by using lower decoupling capacitance values. Then, using wide-band antennas, the radiated electromagnetic and magnetic fields were measured at a distance of several meters in an anechoic chamber. Although the extent of this test is not comparable to the ECSS requirements, it provided a good starting point for estimation of the emissions of the satellite.

The EPS successfully passed the qualification and acceptance test campaign. Only one critical failure happened during the TVC of the EQM.

A ceramic capacitor cracked and generated a critical short-circuit on a battery power line. This overcurrent induced the melting of a battery wire. After analysis, it appeared clearly that it was a manufacturing defect.

Table 7: Results of the radiation tests

Tested items	Tested dose	Results
Sun Sensor	52 krad[Si]	Not affected
COM board	42 krad[Si]	Not affected
EPS-Power management board	35 krad[Si]	µC not affected Beacon signal generator not affected Voltage reference affected (3.25V instead of 2.5V) Power consumption increased of 20%
PL board	29 krad[Si]	CMOS detector affected, but stays within the requirements up to 17 krad[Si]

Note also that during the TVC, both the EQM and FM begun with a cold start (-55^{o}C measured on the frame and the PCBs). Batteries were totally discharged in order to switch off the satellite. When switching on the sun simulator, the satellite started-up without any problem.

Lessons learned

Latch-up mitigation circuitry has not been implemented in the satellite. Several semester/master projects were spent on latch up protection design, and they firstly showed that it is difficult to have a latch up protection at the subsystem level as planned at the beginning of the project. A latch up protection is more effective when it is designed at the component level (or for a small group of components) because the more components we have, the more difficult it is to detect the current increasing on the power line. Consequently, it is necessary to precisely know the consumption of each component that must be protected and find a custom-made protection for each of them separately. The major part of the SwissCube electrical design was done with CMOS based components (which are more sensitive to high energy particles). It is therefore impossible to protect every component. These constraints forced to select some of the components that have to be protected such as microcontrollers that are more susceptible and more critical for the mission. Commercial off-the-shelf components were not found to perform this function with a good accuracy and reliability. Another solution was not found either early enough in the design phase. This is the raison why it was decided not to protect the system against latch up and to rely on redundancy.

From the power point of view, hard efforts have to be done on trying to minimize the resistance of the chain going from the batteries and the solar cells to the subsystems to avoid big voltage drop and loss of energy. Although this question was a decisive factor in the design, it was difficult to maintain this resistance at a very low value.

Regarding the mounting of electronics, a lot a lessons has been learned especially on meticulousness. For example, it is imperative to perform a scrupulous visual inspection after the soldering process to avoid bad solder joints and solder bridges. On SwissCube's electronics boards, some of these bridges were observable only with a binocular. Likewise, when using conformal coating on RF components it is important to be very careful with the oscillators. On the SwissCube Beacon board, adding some conformal coating on a small inductance modified the oscillator frequency and made the board not working anymore.

Regarding the design phases, think as early as possible on how subsystems and the entire system are going to be integrated (integration procedure). Do not only think how it is going to be assembled but also how it is going to be disassembled in case of problems.

ATTITUDE CONTROL AND DETERMINATION

The requirements for the Attitude Determination and Control Subsystem (ADCS) subsystem are driven by the science requirements. Each captured image had to be pointed with a precision of ±[5]° in latitude, ±[7.5]° in longitude (which can be correlated to the solar local time at zenith). If an accuracy of 5° is assumed on the orbital position of the satellite, the required accuracy for attitude determination is therefore listed as ±[12]° along the satellites pitch and yaw axis, and no requirement along its roll axis (which is aligned with the sensor). The integration time on the payload required a pointing stability of the satellite during science observations of ± 3°/s for limb measurements and ± [1.25]°/s for zenith measurements for all three axes.

The ADCS is the system that has had the most changes during the overall development of the satellite. At the beginning of the project, a complete 3-axis control was expected. This should have been achieved using only three magnetic coils (magnetotorquers) and one inertial wheel.

After the preliminary design review, it was decided to simplify the ADCS by removing the inertial wheel. The control requirements were also relaxed, since full 3-axis control was not required anymore by the science. It was decided to detumble the satellite only, when keeping the 3-axis determination. At this point, most of the ADCS sensors used were changed because they were not satisfying the determination precision requirements. Finally, during the last developments steps, it was decided to move the onboard determination to the ground segment because the embedded computer (CDMS) was not fully functional (one of the main task of the CDMS was to run the determination and control algorithms).

The final architecture of the SwissCube ADCS is shown in Figure 15. The sensors used are:

- Three ADXRS401 MEMS gyroscopes.
- Six DTU sun sensors.
- One 3-axis HMC1043 magnetometer.

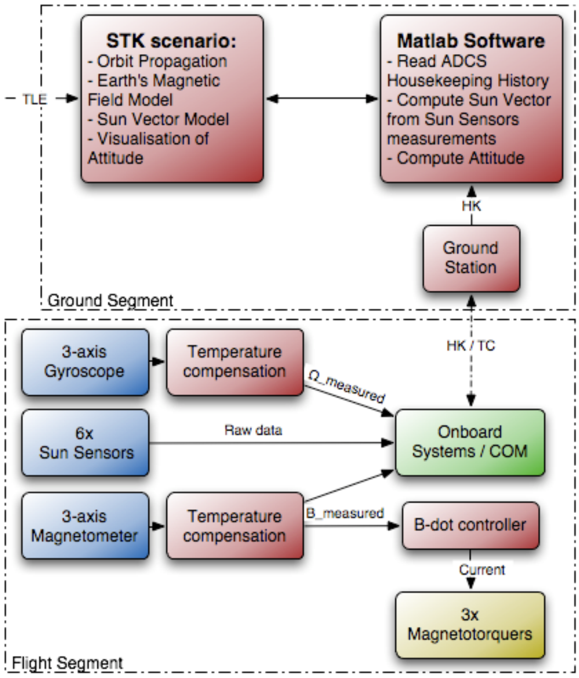

Figure 15: Architecture of final ADCS

The actuators are three magnetotorquers. The detumbling is achieved with an embedded B-dot controller. The gain value of the controller was identified by simulations. In order not to disturb the sensors measurements, time slots are allocated for measurements and actuation. All sensor measurements are temperature compensated onboard and then are sent to the ground station. The satellite determination is performed on ground using specific software designed with Matlab and STK. During the development phases, each sensor was individually characterized. A great care was taken during the testing of the magnetometer, since it is the main sensor for the B-dot controller.

Throughout the qualification and acceptance testing of the ADCS, a temperature dependant hysteresis was discovered in the gyroscopes offset i.e. when the sensor endures a temperature cycle then the static output after the experiment differs from the one before performing the cycle. After a certain time, the output is again the same. Unfortunately, this behaviour could not be fully characterized and therefore the gyroscopes are unable to resolve low rotation velocities. The uncertainty on the gyroscopes measurements is about 5°/s. Note that this behaviour was seen on other MEMS gyroscopes and is clearly a limitation for this kind of sensors. This technology is slightly sensitive to acceleration and therefore gravitation force, which has to be taken into account if very accurate measurements are needed.

The correct behaviour of all ADCS sensors and actuators was tested on the final satellite in order to avoid any malfunctioning or sign inversion. The B-dot controller was checked by applying a rotation to the satellite and measuring the magnetotorquers commands.

Since the size and power consumption are very limited on a CubeSat, the choice and characterization of the sensors remains one of the big challenge for the ADCS. Especially, it has been very difficult finding adequate gyroscopes.

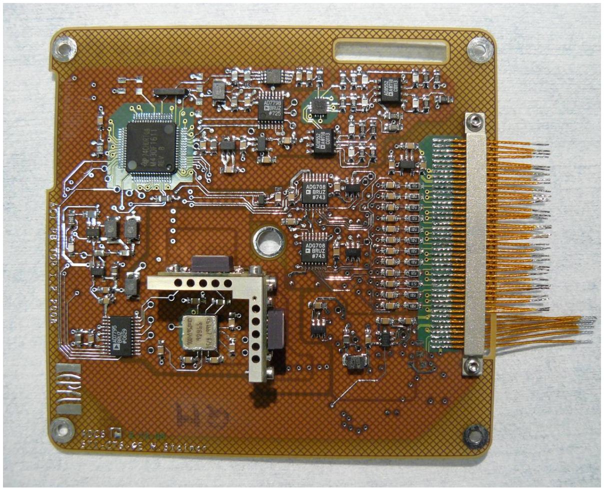

Figure 16: ADCS FM board

SATELLITE COMMUNICATION SYSTEM

Overall communication system description

The communication system is composed of two main parts: the SwissCube spacecraft and the Ground Segment (see Figure 17).

The ground segment is composed of an EGSE router, a TMTC Front End, a Mission Control System, a Scheduler, a Mission Data Client and a Planning Tool. Its purpose is to manage the data that is sent to and received from the SwissCube satellite. Its particular software will be described in the Software section.

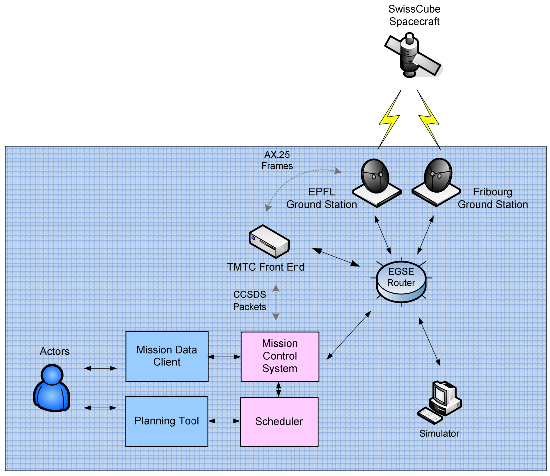

Figure 17: Space-to-ground communication architecture

SwissCube has two ground stations, one at EPFL and one at the HES-Fribourg. Both are redundant and handle the modulation/demodulation of the data, and manage the start/end flags of the AX.25 frames along with the bit stuffing. The ground segment handles the rest of the AX.25 protocol, along with the CCSDS PUS protocol. The EPFL Ground Station has a stack of 4 Yagi UHF antennas for the downlink signal and a stack of 2 Yagi VHF antennas for the uplink.

On-board communication system

The SwissCube satellite has two main communication links. The first link the high-power and high data rate RF link (uplink and downlink). These two signals are located on the COM board. The second link is the low-power beacon signal in Morse code, generated by the EPS board and transmitted by the Beacon board (the signal is also hardware coded on the EPS and thus a failure of the EPS microcontroller still allows to send a beacon message). Figure 18 shows the high level architecture of the on-board communication system (hardware beacon not showed).

The beacon will operate constantly and be switched to the data transmitter once above a partner ground station. The data transmitter on the COM board sends the scientific and engineering telemetry at 1200 bits/sec. The board has been tested. It generates an RF output power of 30 dBm (1W) and modulates the signal in FSK at a frequency of 437 MHz. The design allows for a link margin of 10 dB on a 1000-km circular orbit. The beacon sends only simple housekeeping data at 10 bits/sec in Morse code also at 437 MHz. The beacon signal is transmitted at 20.8 dBm (120mW). Both the beacon signal and the main data downlink signal are connected to a RF switch for transmission to the TX antenna. The uplink signal uses the 145 MHz carrier frequency and is modulated using AFSK.

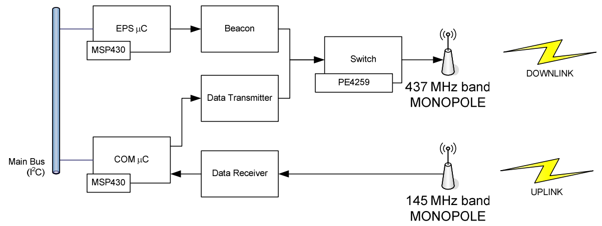

Figure 18: Simple block diagram of the SwissCube onboard communication system

As shown in Figure 19, the COM board manages both the uplink and downlink signals, i.e. demodulate the AFSK uplink signal, modulate the FSK downlink signal and can encapsulate and decapsulate AX.25 frames. The receiver design is based on a dual-conversion receiver architecture, which in a nutshell means the received frequency is down-converted twice before demodulating the message signal from the carrier. For transmission, the data is used to drive the FM modulator through the microcontroller's DAC. The generated FM signal is then passed through a power amplifier.

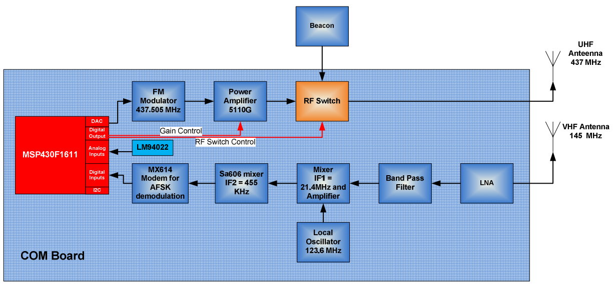

Figure 19: Block diagram of the COM board

SwissCube antennas

Modeling of the antennas length, satellite backplane material and position on the satellite panel was performed and several solutions were analyzed. The chosen antenna configurations include a quarter-wavelength monopole antenna for 145.8 MHz and another one for 437.5 MHz. Both antennas are made of beryllium copper.

Several tests were performed on the antenna deployment system and on the effect of the bending of the antennas on the RF pattern.

The VHF antenna is 610 mm long when the antenna is in straight ideal position. The maximal gain is about 2.25 dBi and the return loss (S11) is -15.3 dB taking into account bending of the antenna.The UHF antenna has a length of 176 mm. Its gain is 3.15 dBi and the S11 parameter equals -16.44 dB.

Description of qualification and acceptance tests

Qualification and acceptance tests both included link budget verification between the SwissCube model and the ground station in Fribourg.

Functional tests consisted in verifying that the RF link between the test equipment and the SwissCube QM or FM is functional.

Characterization tests consisted in observing the RF link and monitoring important parameter such as temperatures, frequencies, received power, and housekeeping values.

Link budget verification consists in making sure that the theoretical link budget is correct, by simulating the predicted losses with attenuators. This test is done to verify that the satellite can receive the uplink signal correctly and transmit with enough power to be correctly received on Earth.

Link budget verification

To verify the link budget, both the EQM and FM the FM were placed remotely (on a mountain peak 30 km away) from the ground station in Fribourg. Uplink and downlink communication was established, and attenuators added on the ground station to simulate the theoretical link budget.

Results were encouraging but not excellent, as the FM had trouble receiving the uplink signal, and the downlink signal was too corrupted to be decoded correctly. Tests showed that there were too much RF interferences at the FM location on the peak, due to GSM and relay antennas nearby.

Further tests on the FM ensured that correct signal reception and transmission is guaranteed even with moderate RF interferences (40W signal on nearby frequency at 1m distance).

Characterization tests results

During thermal vacuum cycling, several parameters such as downlink frequency, downlink power, beacon frequency, and beacon power were monitored. The uplink power was equal to that which the satellite will receive in orbit. Main COM telecommunication occurred during thermal plateaus, at 60°C, 37°C, 20°C, 5°C and -24°C. These communication windows lasted 8 to 10 minutes.

As expected, the beacon frequency varies depending on the temperature. The frequency varies by 10.86 kHz. It's a much greater variation than expected (4 kHz), but it still is admissible.

As for the main downlink signal, the highest frequency deviation at a given thermal plateau is 4.24 kHz. The frequency variation as a function of temperature is not linear. As such, the variation can be positive or negative depending on the temperature. The greatest variation of the downlink signal power occurs during the plateau at 60°C where the signal's power looses 4.7 dB (nominal operations should be around 40°C). This is due to the overheating of the COM's power amplifier (PA). When the environment is already at 60°C, the power amplifier goes to 96°C and regulates itself to reduce the output signal's power. It is to be noted that a thermal sink path is placed between the back side of the PA and the satellite frame.

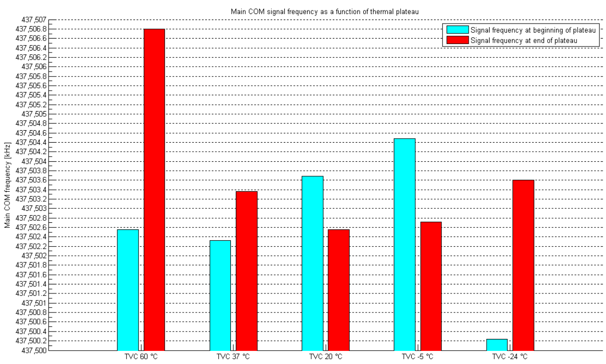

Figure 20: Downlink frequency as a function of thermal plateau

Lessons learned

Go for design simplicity when possible. The uplink receiver onboard is a simple design, yet it is very durable and allows for great uplink frequency variation.

Make a robust design so that the downlink frequency is not too influenced by the board's temperature.

Use high efficiency power amplifiers, in order to increase the power output or decrease the power consumption.

Aim for a complete separation of the beacon and downlink RF paths.

GROUND AND FLIGHT SOFTWARE

Space to Ground data link

The data link follows common usage in network protocols with data packets encapsulated in data frames to optimize bandwidth usage with packets of different sizes. It was decided from the start to follow ESA's standards for the telecommand and telemetry packets, therefore the ECSS-E-ST-70-41 Packet Utilization Standard or PUS (standardized the services and usage of *CCSDS Packets*) is used. This was motivated by desire of being compliant with the same standards as the space industry and for cooperation with ESA. At the frame level, compatibly with the radio amateur equipments was required; hence AX.25 transfer frames were chosen. They were adapted with the addition of new fields for functionalities found in space protocols such as virtual channels, time correlation, frame loss detection, data sequencing, etc. This allows having both the ground and space systems following ESA practices and while using an Amateur Radio compliant physical link.

Ground software

The ground software architecture is shown in Figure 21.

EGSE Router (as seen in Figure 17). This simple but central software provides standardized communication between all the components of the ground segment described hereafter. It is not a component of the ground segment but of the communication infrastructure itself. It is based on and compliant with a well-defined protocol that allows exchange of telecommand-/telemetry packets/frames and custom data between clients. This protocol was developed by ESA as part of the EGSE Reference Facility effort.

Mission Control System. This is the main component of the ground segment, it is responsible of the telecommand packets generation and processing of telemetry. It is compliant with a major subset of the PUS standard and was not designed as a *SwissCube MCS* but really as a *PUS MCS*. In fact its design and implementation phases started well before those of the flight software. It is reusable for any PUS-compliant mission. In addition to the PUS packet interface, it exposes a distribution interface used by the pass scheduler and mission data clients that provides both real-time data using push technology and access to all historical data. It also exposes an uplink interface that allows other components (such as the pass scheduler) to request telecommand packets generation from a simple definition (e.g. name of the telecommand packet and list of non-encoded parameters).

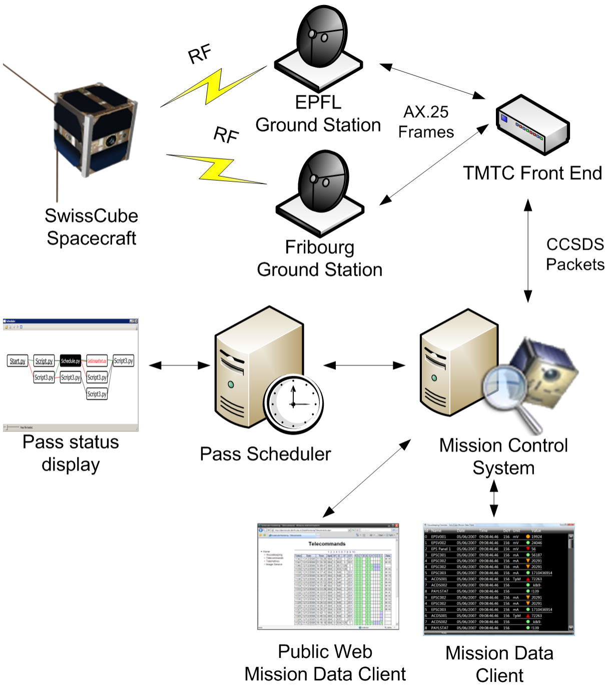

Figure 21: Ground software architecture

TMTC Front End. In-between the ground station and the Mission Control System, the TMTC Front End serves as an interface between the PUS and AX.25 segments. It encapsulates telecommand packets into AX.25 frames and processes the telemetry by doing packets reassembling, frame loss detection, replay of received telemetry frames, etc.

Ground Station Software. In contrast with other ground segment components, most of the software that makes up a ground station was not designed nor developed in-house. Instead widespread Amateur Radio software is used. HamRadioDeluxe takes care of the satellite tracking and frequency Doppler correction. MixW processes the audio signal coming out of the transceiver and decodes the AX.25 telemetry frames. Small programs still had to be written to control the antenna rotors, control the uplink TNC and connect MixW to the TMTC Front End through the EGSE Router.

Pass Scheduler and Pass status display. The pass scheduler provides scripting capability to program the logic of the actions that will occurs during the spacecraft pass over the ground station. The pass status display is its decoupled graphical user interface.

Mission Data Clients. There are two versions of mission data clients. The first is a stand-alone application with real-time display and advanced graphical user interface. This is the one used by operators for both tests and operations. The second version is a web-based client with less data (e.g. no telecommand information) and oriented for public usage.

Flight software

The flight software of all the subsystems is based on a common codebase that provides time synchronization, I^2C bus connectivity, remote function calls and housekeeping reporting (see final architecture in Figure 22).

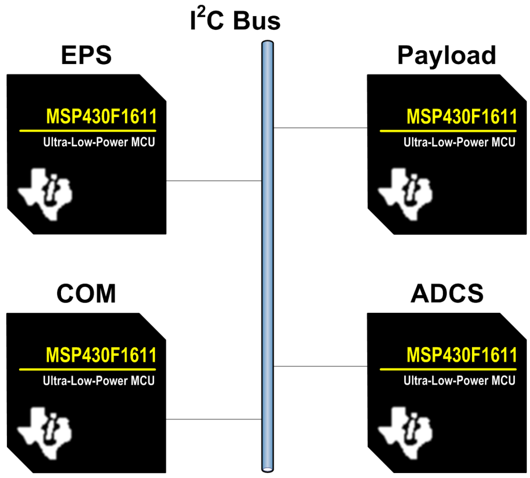

Figure 22: computing architecture

The following PUS services are exposed by the spacecraft (for more information on first three of them, see the ECSS-E-ST-70-41 standard):

1. Telecommand verification service. This service provides the capability for explicit verification of each distinct stage of execution of a telecommand packet, from on-board acceptance through to completion of execution. In this sense, it is a supporting service for the telecommand packets (service requests) belonging to all other standard and mission-specific services.

3. Housekeeping data reporting service. This service provides the capability of reporting the housekeeping parameters in accordance with a set of reporting definitions stored on-board. For SwissCube, only the static housekeeping reporting subset with all definitions fixed before the mission operations is supported.

8. Function management service. This service provides the capability of supporting software functions that are not implemented as standard or mission-specific services but whose execution may nevertheless be controlled from the ground.

128. Payload management (mission-specific). This service was specifically designed for the operation of the onboard payload. It exposes all the means to command an image capture and to retrieve captured images along with their associated information.

As each subsystem has its own microcontroller, the flight software architecture is very similar to the electrical one. All the boards run the same microcontroller from TI and almost all the code is written in C with some exceptions for the payload with parts in assembly. They don't use an operating system, but due to their significant interaction with the hardware the flight software is not all that easy.

EPS. This is the main subsystem of the spacecraft with the most functionality implemented on it. Not only does it control the power of the others subsystems, but it also has to monitor the health of the spacecraft. To do so, it checks specific measurements on the EPS board and also checks the responsiveness of other subsystems. Also as master of the I^2C bus, it reads the housekeeping of the others subsystems when requested by the ground via telecommand. EPS generates the software beacon message as well, which contains a small amount of housekeeping data in contrast to the hardware beacon which is only composed of the spacecraft's callsign. The EPS exposed all the aforementioned PUS services to the ground.

COM. As the entry point of the space segment, this subsystem decodes the AX.25 telecommand frames and processes them verifying both the integrity of the frame itself and the contained telecommand packet. Its second major role is the sequencing of the telemetry packets so that bandwidth usage can be optimized. It's the only subsystem that is frame-aware. The COM subsystem exposes all three standard PUS services to the ground (1, 3 and 8) so that it can communicate directly with the ground in a stand-alone manner.

ADCS. The flight software of the Attitude Determination and Control Subsystem is mainly composed of the detumbling software. The subsystem does not expose any PUS service, only housekeeping retrieval and function calls from the I^2C master, in fact it is not PUS-aware at all.

Payload. As with ADCS, almost all the flight software consists of the specific role of the subsystem with no PUS service exposed. The onboard code manages the CMOS detector and the external RAM used to store a captured image. Only the EPS interacts with the payload and does it by using the common function calls and housekeeping retrieval codebase.

Each subsystem was tested individually before integration and then with the complete system. During the TVC tests, all verifications of the spacecraft's health were done through the exact same mechanism and protocols as in operations. Scripts for the pass scheduler were written for the tests to use all functionalities of the spacecraft and check the results.

Test results

While the tests uncovered a few bugs and errors, they could be corrected and all functionalities of the satellite worked successfully.

Lessons learned

Implement and test communication bus early. The choice of the communication bus has enormous implications on the choice of the microcontrollers and to the flight software's system architecture. It is very important that all aspects of the communication bus are known, including its less-documented short-comings. The I^2C bus was chosen early in the project without fully understanding it. As a result it was discovered only later the impossibility to implement reliable multi-master communication with correct subsystem isolation and therefore the whole flight software architecture and data flows had to be adapted.

Use the same software for tests and operations. In contrast to most software projects, the implementation of the ground software was started before the flight software. This was possible through the compliant usage of the ECSS-E-ST-70-41 packets. The developed Mission Control System software is capable of generating and processing packets not specifically for SwissCube but for almost any small spacecraft mission compliant with the same standard. That allows not only having the ground software ready before flight software and be able to more easily test the latter with the former, but also to fully understand the standard's intricacies and then make a good tailored version easy to implement in the flight software. This is also a big investment as all future space projects will be able to reuse the same Mission Control System by needing only reconfiguration and mission-specific additions (which can be added in the forms of plug-ins).

Plan big for flight software tests. Keep in mind all the functionalities of the spacecraft need to be able of to be tested remotely and that the results should be easily seen. And all that will be done a lot more than once. Much time will be loss if sending a specific telecommand takes more than clicking a button. Having the ground segment software ready for the tests is of great help as the pass scheduler can be also used to send the test telecommands.

Implement remote software update capability. This is something that was unfortunately not implemented on the SwissCube spacecraft but would have been a huge advantage. When reviewing the inclusion of this functionality, only updates while in space during the mission were thought about and not deemed to be a priority. But as discovered latter, it goes well beyond that. Being able to update the flight software during tests without needing physical access to the spacecraft is a real need. Many tests are done with the spacecraft not accessible, such as vacuum or thermal testing. In these situations if minor flight software bugs are detected, they can't be corrected without stopping the tests. Therefore they have to be fixed consequently and the spacecraft need to be retested again, which results in a loss of time.

Build modular ground segment software. Each piece of the ground segment should be well defined by ICD's and easily replaceable. As an example, the spacecraft's uplink and downlink (digital, in-between the modem and the microcontroller) can be connected via its test connector to a test board. This allows testing of the complete flight software, including the AX.25 stack without needing any radio equipment. The solution is to simply build another piece of software that connects to that test board and exposes the same interfaces as a ground station (reusing a lot of shared libraries). The rest of the ground segment has no awareness of this different data link and no modification is required.

SWISSCUBE STRUCTURE

The SwissCube structural design is described in more detail in a previous publication[2]. In a nutshell, the SwissCube structure is compatible with the CubeSat standard, including access ports and deployment switches. The configuration accommodates all platform elements, the optics payload and the antenna mechanism.

Different structural frame options were studied during the early phases of the design. A "monoblock" approach was selected based on weight constraints and structural strength considerations. This concept has the disadvantage of increasing the complexity of the satellite's assembly procedures. This lightweight monoblock frame also serves as a secondary structure, for the attachment of the Payload, PCBs or external panels. The frame is machined using first milling and then Wire Electrical Discharge Machining (WEDM) for machining of the internal volume.

The final mass of the structure is 94.5 grams, probably one of the lightest in the CubeSat community. The Engineering Qualification Model (EQM) structure with both surface treatments is shown in Figure 23.

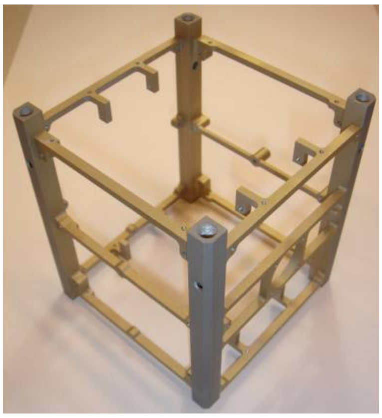

Figure 13: SwissCube Monobloc Frame (EQM)

Mechanical tests and results

In October 2008 the SwissCube Engineering Qualification Model (EQM) passed the mechanical qualification tests campaign at DLR-Berlin (Germany). The test levels for the three axes were 4.5 [g] between 8 and 100 [Hz] for the sinusoidal test, 6.7 [G_{rms}] for the random test and 4'500 [g] at 10 [kHz] for the pyroshock test. The EQM successfully passed these various mechanical tests without problems.

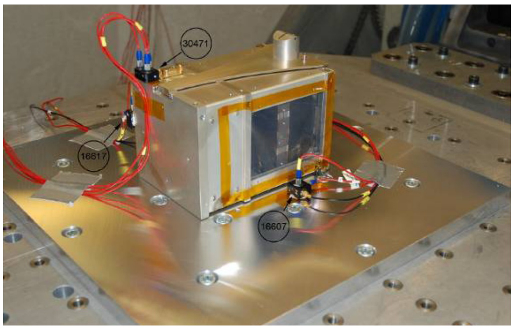

Figure 25: Set-up for X-axis random test of the FM

The SwissCube Flight Model (FM) went through the mechanical acceptance tests campaign in January 2009 at the University of Bern (Switzerland). The test set-up is shown in Figure 25. The acceptance test levels were 3 [g] between 8 and 100 [Hz] for the sinusoidal test and 4.5 [G_{rms}] for the random test. The FM successfully underwent these various mechanical tests without problems. Resonance survey tests before and after running each test at full level have been made to compare the results for any possible damage to the S/C during the full-level tests.

Assembly procedure and cabling

The assembly procedure of the satellite must be planned as earlier as possible in the mechanical design. On SwissCube, the purpose was to facilitate the troubleshooting on the electronics boards as far as possible. And this goal has been reached. The internal electrical system of the satellite can be extract of the structure with a minimum of manipulations. This was extremely helpful when it was necessary to replace a component or make a measurement on inaccessible areas.

Evidently, the assembly procedure must also consider the cabling aspects. Thanks to a well defined cabling design, a lot of time was saved during the testing and integration phases. The cabling process was simple and easily reproducible.

Lessons learned

In comparison with typical CubeSat that have structures made of many parts screwed together, SwissCube structure is much complex and sophisticated. The "monoblock approach" was earlier selected due to the best relationship between mass and rigidity. On the other hand the main drawback of this type of frame concerns the subsystems configuration. Of course such a structure makes sense only for satellite in the pico to nano-size. The "monoblock" involves a completely different way of ordering spacecraft subsystems and this should be taken into account from the beginning of the design.

CONCLUSIONS

This paper presents management, mission and subsystem lessons learned for the SwissCube project. Overall, the design of the payload, power system and communication system is very satisfying and reliable. The structural design is very light and robust, and allowed for efficient integration of the subsystems. The data management board suffered delays in the software and thus will be flown cold. The attitude determination system can definitely be improved in the next version of EPFL CubeSat. But this project has been an excellent educational support that promoted not only technical skills, but also team building, initiatives, responsibility and good humor.

Acknowledgments

The SwissCube project would like to acknowledge its sponsors without which none of it would have been possible (RUAG-Aerospace, EPFL, Swiss SSO, Loterie Romande). We would like also to thank the laboratory supervisors and technicians that have actively participated and very often provided the final push necessary to get a functional hardware. We would like to thank as well RUAG-Aerospace and the University of Bern for their test facilities.

We also thank the AAU and Delfi C3 CubeSat teams for their active and fruitful participation in the reviews during the whole project.

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