Lessons learned from building the first Chilean Nano-satellite: the SUCHAI project

Carlos Gonzalez, Camilo Rojas, Alex Becerra, Javier Rojas, Tomas Opazo, Marcos Diaz.
Space and Planetary Exploration Laboratory, Faculty of Physical and Mathematical Sciences, University of Chile
Beauchef 850, Santiago; 569-75535716.
carlgonz@uchile.cl

ABSTRACT

This work presents the preliminary results and the lessons learned from the operation, thus far, of the Satellite of the University of Chile for Aerospace Investigation (SUCHAI-1), the first CubeSat mission at the University of Chile. The development of the SUCHAI-1 started in 2011 and was launched in June 23rd 2017 in an Indian PSLV Rocket. The launch resulted in a circular polar sun-synchronous orbit at an altitude close to 505 km. The SUCHAI-1 has operated continuously for more than 12 months except for three days after the mid-September 2017 solar storm. The SUCHAI-1 has been studying the capabilities that CubeSats can offer for scientific missions and collecting data from on-board payloads. This project has been the seed for a much longer space program at the University. Currently two other CubeSats are under construction. In this work, we describe the difficulties and the advantages of developing a nano-satellite project in a developing country and the impact that this project has had in students as well as in the space area in Chile.

INTRODUCTION

Chile is an attractive place for much of the space activity, mainly due to the geographical location and distribution. For instance, astronomy is an extremely active field within the country. Early Chilean space activities began with satellite tracking stations. In 1959, the University of Chile created the *Centro de Estudios Espaciales* (Center for Space Studies) as part of an agreement with NASA to assist with satellite tracking. This became the center's specialty for over 40 years, supporting many NASA missions including those in the Apollo series [1]. Since the 90´s the space activity has been managed by the Chilean Air Force, which has purchased three Earth Observation Satellites: FASAT Alpha, FASAT Bravo and the SSOT (also known as FASAT Charlie). Although, operating a purchased satellite is a natural manner to start a space activity, the next level of development should be the design and construction of a satellite within the country. Explanations aside, the fact is that Chile has been in space without a strong determination. This fact is reflected in the lack of a long-term space policy and agency to execute it or help to execute it. Usually, developing countries should find strong grounds to justify a spent in creating space capabilities, especially nowadays where most of the space services can be purchased as commercial services. The lack of state determination and the emerging CubeSat paradigm were perceived as a necessity and an opportunity at the University of Chile, respectively. Thus, in 2009 the idea of developing a seed project based on CubeSat technology came to live.

Satellite of University of Chile for Aerospace Investigation (SUCHAI) started as a concept in 2009. For mid 2010, a detailed plan and engineering design were developed. The funding started in March 2011, which came in its totality from the Faculty of Physical and Mathematical Sciences at the University of Chile.

At the start of the project, Colombia was the only country in Latin America that had launched a CubeSat [2]. In the following years, while SUCHAI was under developing, Peru [3], Brazil [4], Ecuador [5], Uruguay [6] and Argentina [7] launched their own CubeSats. The feedback provided by these missions was extremely useful, since it allows us to learn from previous experiences within the region. South American countries, in particular, Peru, Ecuador and Uruguay are countries similar to Chile in the state of development of their own space programs.

Within this work, we provide a summary of what we have learnt from the development, launch and operation of the first Chilean made nanosatellite, the SUCHAI project. With this we expect to facilitate the development of university space programs in developing countries, improving the number of contributions to space exploration of less experienced countries.

DECISIONS WITHIN THE PROJECT

The SUCHAI CubeSat is a seed project. Consequently, was conceived as a proof of concept for a university program [8]. Although, the idea of passing from one CubeSat to a space program was not guaranteed, many of the decisions were made to accomplish this goal. Thus, the project was based on three main pillars which could guarantee a level of success for the project by continuing this type of activities: (1) Human capital formation, (2) Knowledge generation and (3) Performing a project of this magnitude in a limited time and budget scenario. With this in mind, the milestones and requirements of the project were conceived.

Milestones

A clear relation of the pillars of the project with its milestones is needed to retain the focus of what is being done and pursued. We had to find a balance between creating a project from scratch and reuse foreign teams experience to reduce mission risks but still acquire valuable knowledge for future missions. With this tradeoff in mind we defined the following milestones:

1. To design a 1U CubeSat.
2. To request and obtain most of the permissions for the construction and operation of a 1U CubeSat.
3. To build a 1U CubeSat.
4. To test (within the laboratory and for qualification process) a 1U CubeSat.
5. To manage the process to launch a 1U CubeSat.
6. To make contact with the CubeSat (to hear the beacon).
7. To operate in space a 1U CubeSat.
8. To perform research with a 1U CubeSat.

The previous milestones where subject to three major restrictions which usually were in counter position:

1. To accomplish the previous steps involving young, in formation, engineers (mostly undergrad engineering students)
2. With a budget below USD 300,000.00
3. Within a time frame of 2 to 4 years.

Human Capital

We wanted to educate engineers and scientists with the project, starting a space program without previous knowledge and with limited time and budget. Therefore, the solution was a focalization. We decided that we could educate engineers and scientists in three major areas: (1) CubeSat design with COTS components, (2) flight software and (3) payloads for space physics research.

Knowledge Generation

The lack of experience was conceived as an opportunity. Each unknown was treated as a learning possibility not only to study the current state of the art of the knowledge but also to suggest hypotheses and experiments to test those hypotheses. CubeSat platform imposes strong restrictions to do interesting things in space which is a natural driver for education, research and innovation. Example of these reasoning are the following experiments: electronic in hostile environment, temperature distribution, attitude determination procedure, estimation state of health of the batteries and electron density (Langmuir Probe) and particle counter monitoring.

Budget

The total budget of USD 300,000.00 was divided grossly in three parts. Approximately USD 110,000.00 were for the launch, another USD 70,000.00 for the three-year salary of a young engineer, and the last USD 130,000.00 for the Laboratory set up, the hardware of the CubeSat and payloads, for the setup of the ground station and for the qualification tests. The educational approach of the project implies that an important part of the man power was developed by students that integrated the development of the satellite in their own engineering curricula.

Versionized and Agile approach

Due to the lack of previous experience in this type of project within the team, we decided to follow a path of agile trial and error approach [9, 10]. Thus, the preliminary engineering designs had to satisfy a minimum requirement. Then, the design is developed and integrated. If the integration and tests are successful, that version of the component, payload or experiment is defined as *ready to fly* and properly stored. Only in this point we might start a new improved version of the component. In this manner, we were finding the issues and problems fast and solving the simple version first, intending to always have a satellite ready to fly. For instance, we first had a “sputnik” version satellite, that is: the main bus capable to send a Morse code beacon. Then we scaled the capabilities of the satellite through time. This approach imposed a strong requirement to the bus, payloads and flight software architectures. The requirement was the capability of extending features and/or exchanging payloads in an extremely rapid way. For this reason, we focused on the flight software architecture and decided to make it highly modular, flexible, and scalable.

For the mechanical parts, we took advantage of digital fabrication. Digital fabrication allowed to test parts in fast ways. For prototyping we used common materials such as Aluminum, PLA and/or ABS. However, the flight versions were made in Windform XT2.0 and Ultem 1010. Figure 1 shows samples of the camera and Langmuir probe support made in different materials during the development cycle of the SUCHAI.

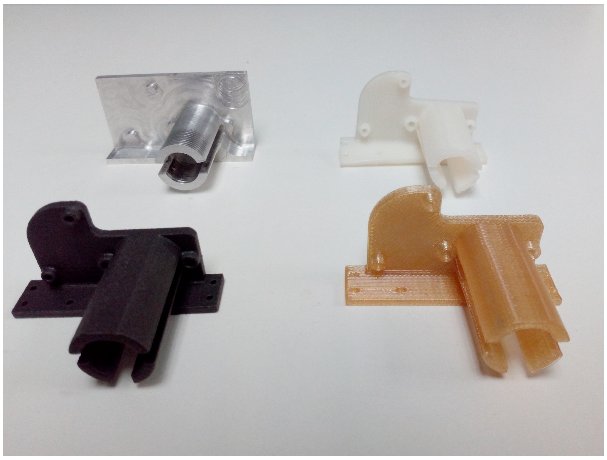


Figure 1: Prototype of the camera and Langmuir probe support. In aluminum, ABS, Windform XT 2.0 and Ultem 1010.

SUCHAI DESCRIPTION

CubeSat components and architecture

SUCHAI is a 1U CubeSat nanosatellite based on a Pumpkins' CubeSat Kit. The BUS consists of a PIC24F as on board computer (OBC), a GomSpace's Nanocom U482C transceiver (TRX), a Gomspace's NanoPower P31u energy power system (EPS) and a custom deployable antenna system. The payloads on board include: a Langmuir probe developed in collaboration with Taylor University, a Javad's GPS, a VGA camera, a custom payload board with four temperature sensors, a gyroscope, two EEPROM memories and a physics experiment. The antenna mount, camera mount and Langmuir probe deployment mechanism include 3D printed structures.

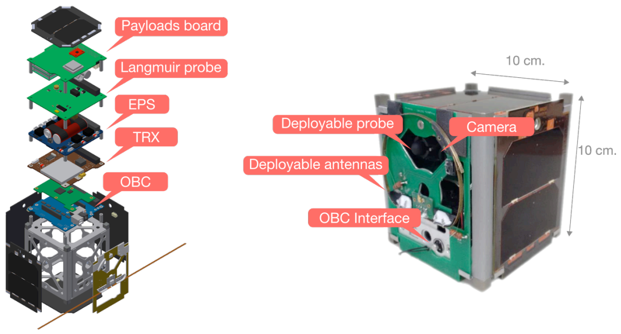


Figure 2: Left: exploded view of the SUCHAI nanosatellite. Right: assembled view of the SUCHAI Nano-satellite

All the subsystems are stacked and connected through the PC104 connector; however different data protocols coexist due to the use of some COTS components. The main bus is composed by the OBC, TRX and EPS. They communicate with each other by using the CubeSat Space Protocol (CSP). The CSP allows to implement a multi-master distributed network between the main bus components and the ground segment via the UHF radio. The OBC collects and stores data from all subsystems, and controls the satellite operations in three ways: on-demand commands from *ground station*, scheduled commands in the *flight plan*, and the *state machine* that controls the payloads operation.

As it was the first space mission of the team, we decided to integrate space proven components from reliable vendors, self-made scientific payloads and COTS components. Instead of building a full satellite from scratch we decide to use some budget to reduce risks and development/iteration times. In retrospective, this decision showed to be appropriate. Therefore, we focused on the flight software, payloads development, integration and tests processes. From the bus architecture perspective, we learned that subsystems connected through multi-master/multi-slave data buses like I2C are more flexible to integrate and should be preferred to either RS232 or SPI as much as possible. Figure 3 presents a simplified scheme of the SUCHAI software architecture. CAN bus is also a good candidate for future missions.

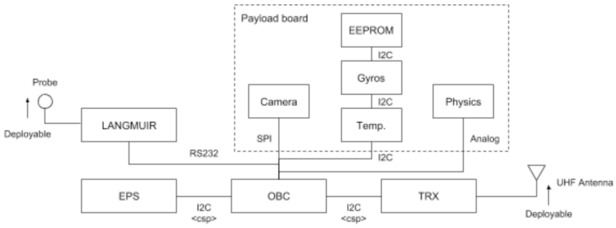


Figure 3: SUCHAI bus architecture

Ground Station

To be able to communicate with the satellite, it was necessary to build a ground segment to send telecommands to the satellite, as well as to receive and store telemetry. In this context, a ground station was designed to comply with the restrictions imposed by the transceiver integrated in the SUCHAI, which transmit in half duplex mode at the 430 MHz band.

The ground station is composed by an ICOM's 910H transceiver capable of operating on VHF and UHF bands together with CW and FM modes. It can be controlled by a remote computer using a serial interface. An M2's antenna in UHF band and a LNA for the same band completes the ground radio system. The antenna is a cross yagi of 42 elements with a minimum gain of 17 dBi and a HPBW of 21°. At first, due to the uncertainty on the link budget and the position of the station, in the middle of Santiago city, that kind antenna was chosen to improve the link. However, it was demonstrated that such antenna is not always a good selection because the high directivity is a drawback in case of pointing errors. For pointing a Yaesu G-5500 azimuth-elevation rotators and controller were chosen. This device provides a 450º azimuth and 180º elevation control. Finally, the GomSpace TNC and the server completes the system that allows to send and receive digital data. Details of the ground station systems and its configuration are presented in Figures 4 and 5 respectively.

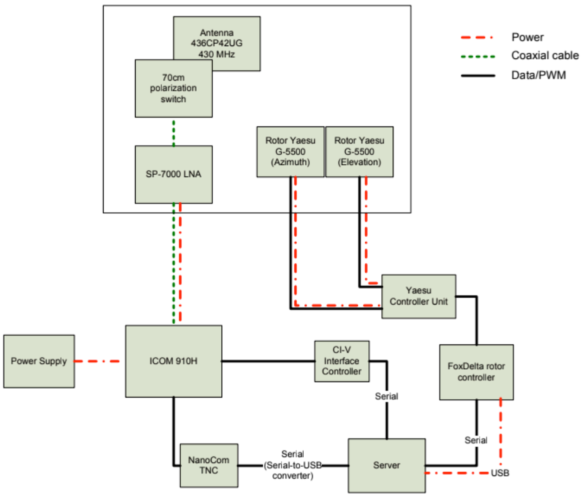


Figure 4: Ground station system diagram.

Figure 5: Ground station equipment.

Two applications are used to control the satellite operations. The first one is GPredict, a free software application, capable of tracking satellites, controlling the antenna rotor and the radio frequency to correct the Doppler shift. The second application is the SUCHAI *Ground Station Software*, that was developed by students of the laboratory as an open source project, and is used to send tele-commands to the satellite, receive and store the telemetry in a database. Figure 6 shows the graphical operating environment of the ground station.

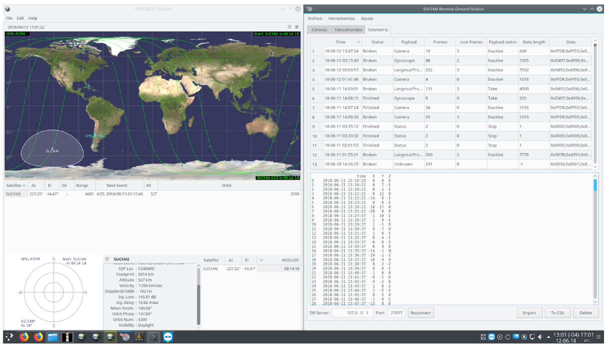


Figure 6: Ground Station Software.

Among the lessons learned during the operation of the ground station, the following can be highlighted: The ground segment has a fundamental mechanical component in its operation, which must have a periodical maintenance protocol. The lack of proper maintenance to the mechanical parts, during the waiting for launch period, had its impact within the first months of operation, where one of the coils of the azimuth rotor was burned. Together with leaving the satellite without optimal communication due to rotor damage, the repair time can be long due to difficulties of finding a spare part of the rotor in local markets. Without a spare part on hand we were forced to repair the damaged rotor to have the ground station back in full operation. During this period of two weeks, we communicated with a smaller yagi antenna, mostly to monitor the state of health of the spacecraft.

Another lesson learned is related of using a radio amateur frequency band. On one hand, it allowed the satellite to be listened in different parts of the world, retrieving the state of the satellite through radio amateurs who could listen to the beacon. But on the other hand, the link is exposed to both interference generated by different users of the band, as well as electromagnetic noise of relevant level by handheld elements used in daily tasks (remote controls, walkie-talkies, etc.).

Integration among different elements in the ground station was not a simple task, but the advantage of using components familiar for the radio amateur community allowed us to take advantage from the radio amateurs experience. For instance, in the beginning of the operation in space of the SUCHAI-1, establishing proper communication with it was difficult. It was noticed by radio amateurs that we were sending tele-commands to the satellite with an incorrect Doppler shift. This happened because we were unable to make the ICOM-910H work together with Gpredict to make the proper correction in the uplink.

Finally, it should be pointed that the station has a LNA immediately after the antenna, which within the operation of the satellite has not been used, because in trying to make it work with the rest of the system, the noise level increases to such an extent that the link with the satellite deteriorates.

Flight Software

We noticed that to integrate all the subsystems and to implement the full set of functional requirements, the OBC flight software is fundamental. SUCHAI flight software was implemented from scratch using the C programing language, FreeRTOS and LibCSP. The main features of the flight software include: execution of remote commands, collection of system status data, command scheduling in a reconfigurable flight plan, automatic sampling of payloads data, telemetry downloading and a serial console to debug the development process. It is a Free and Open Source (FOOS) project that can be found in GitHub and is ready to be compiled for the Microchip PIC24F [11].

The software was designed with modularity and extensibility in mind using design patterns adapted to the C programming language. The software extensibility allowed an iterative development of the satellite's functional requirements. The software modularity allowed an effective team collaboration because modules controlling payloads were easy to integrate, remove or change. Thus, combining these two software quality criteria the team members could divide their work in the main bus features and the payloads development.

The implementation of the satellite flight software was a key element in the SUCHAI project. Most of the integration process and features such as tele-commands, telemetry and fault tolerance are implemented in the OBC software, so that, flight software received special attention. We also learned that modularity in the flight software is key concept to overcome uncertainties in this kind of space projects. In fact, we suffer at least two major changes in the original plan and satellite configuration. The first transceiver we integrated in the bus and in the flight software never operated as expected. Thus, a new and different transceiver was acquired, tested and integrated in the satellite bus and flight software. Later, the battery packs of the first acquired EPS resulted critically damaged as the result of an improper handling. A new and different EPS was acquired and had to be integrated (both mechanically and in the flight software) just a few months prior the qualification campaign.

Laboratory Tests

Due to the high level of integration of the whole satellite system we found that Hardware in Loop Simulation was the most appropriate technique to test the SUCHAI functionalities [12]. The satellite was programmed, assembled and powered simulating the after-launch conditions. We had access to the satellite serial console, then we can analyze the system functioning based on the debug output, modifying by external commands the functioning to simulate the response of the system to external stimulus. The TRX and ground station were also functioning to simulate tele-command and telemetry downloading operations. Finally, based on a simulated orbit we generate a 24 hours schedule that includes: deployment, umbra and penumbra times, payloads operations and ground station contacts. To simulate sunlight and umbra moments, the satellite was connected (charging) or disconnected to the USB interface, respectively. When disconnected the satellite should operate supported only by the batteries. The whole process was recorded, logged and the software output stored and post processed. Figure 7 shows the laboratory configuration of this tests.

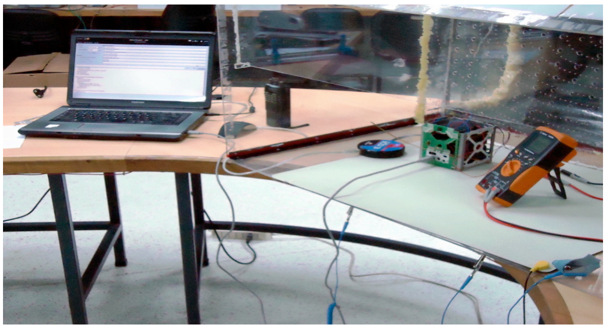


Figure 7: SUCHAI under test using hardware on the loop simulation.

INTEGRATION AND TESTS

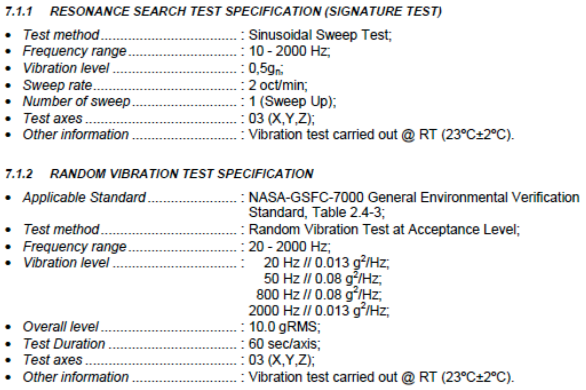
Payloads integration

Payloads are composed by hardware and software. From the hardware point of view payloads should accomplish the3 CubeSat standard form factor restrictions, fit on the PC104 bus, use the available power lines (3.3 V or 5.0 V) and the available communication buses. From the software point of view, payloads should provide driver libraries, example codes and documentation. Payloads programmed and documented as gray boxes that provide a well defined application programming interface (API) can be integrated straightforward in a modular and flexible flight software.

We learned that payloads can be developed parallel to the integration of the main bus, provided that a clear software and hardware architecture are defined. Flight software flexibility is important to integrate and improve the subsystems functionalities during the integration stage. Also, communication over data buses that features directioning and master-slave or multi-master topologies, as the case of I2C and CAN protocols, are preferable. These protocols give more flexibility to add or remove payloads to the satellite. Communications libraries such as LibCSP simplifies the data transferring and command passing both inside the satellite and to the ground segment. Using this well proven library helps to deal efficiently with common problems in communication systems such as framing, routing, errors handling, session management among others.

QUALIFICATION TESTS

We performed the protoflight tests twice [13]. Both tests were performed at LIT-INPE facilities, Brazil. The first test was performed in May 2014 to externally verify that our platform was in conditions to pass the qualification launch tests. These first tests followed the *NASA-GSFC-7000 General Environment Verification Standard* qualification requirements. The vibration and Bakeout tests are summarized in Figures 8 and 10. In Figures 9 and 11 are shown the actual experimental configurations of the tests. Since for the first test the launcher was not actually defined, a mechanical structure available at LIT-INPE as the POD for the vibration test of the satellite was used [14].



7.1.1 RESONANCE SEARCH TEST SPECIFICATION (SIGNATURE TEST)

- *Test method* .... : Sinusoidal Sweep Test;
- *Frequency range* .... : 10 - 2000 Hz;
- *Vibration level* .... : $0,5g_n$;
- *Sweep rate* .... : 2 oct/min;
- *Number of sweep* .... : 1 (Sweep Up);
- *Test axes* .... : 03 (X,Y,Z);
- *Other information* .... : Vibration test carried out @ RT (23°C±2°C).

7.1.2 RANDOM VIBRATION TEST SPECIFICATION

- *Applicable Standard* .... : NASA-GSFC-7000 General Environmental Verification Standard, Table 2.4-3;
- *Test method* .... : Random Vibration Test at Acceptance Level;
- *Frequency range* .... : 20 - 2000 Hz;
- *Vibration level* .... :
  20 Hz // 0.013 g^2/Hz;
  50 Hz // 0.08 g^2/Hz;
  800 Hz // 0.08 g^2/Hz;
  2000 Hz // 0.013 g^2/Hz;
- *Overall level* .... : 10.0 gRMS;
- *Test Duration* .... : 60 sec/axis;
- *Test axes* .... : 03 (X,Y,Z);
- *Other information* .... : Vibration test carried out @ RT (23°C±2°C).

Figure 8: Vibration requirements for the first qualification campaign.

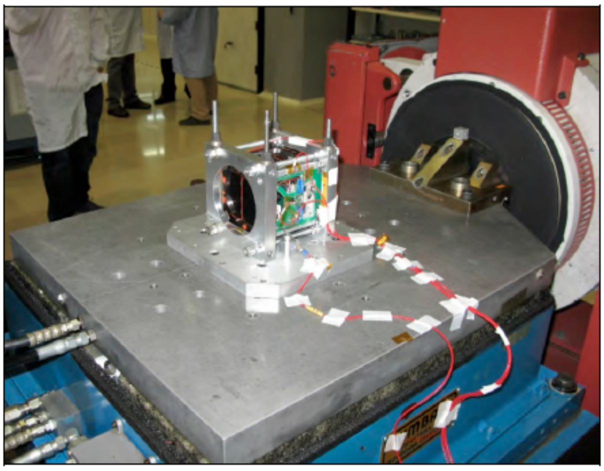


Figure 9: Experimental set up of the vibration test for the first qualification campaign.

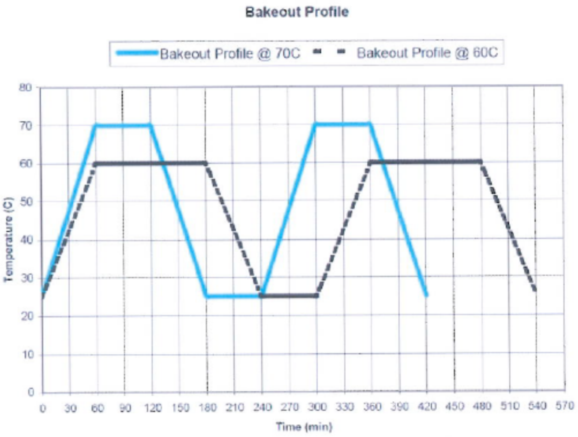


Figure 10: Bakeout profile requirement for both qualification campaign.

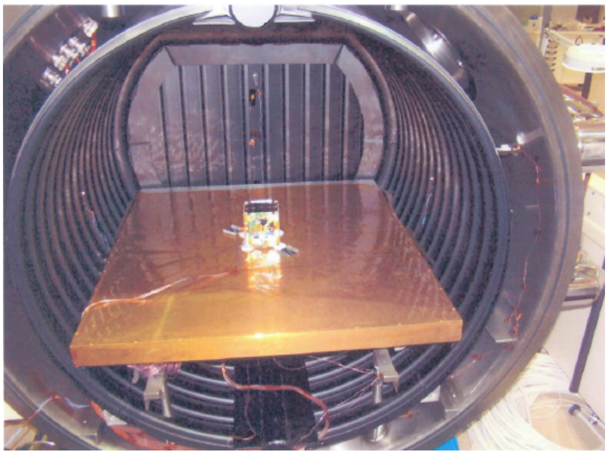
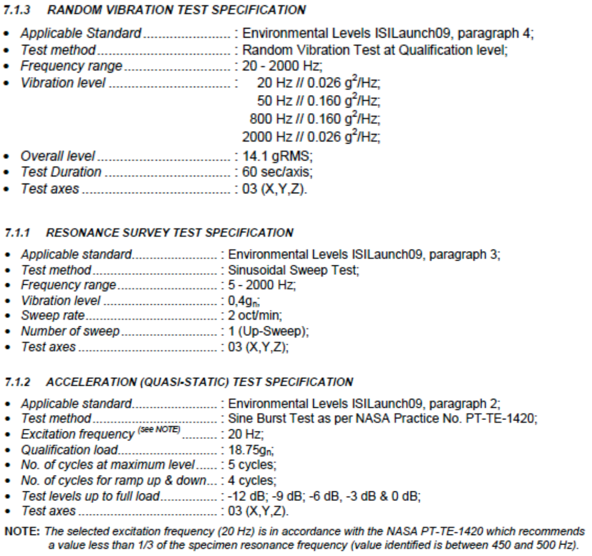


Figure 11: Experimental set up of the bakeout test for the first qualification campaign.

The second protoflight tests were performed in April 2016 also at LIT-INPE, Brazil. The intermediary for the launch was ISL and the defined rocket at that time was the Falcon-9 from Space X, scheduled for launch, for June 2015. The requested vibration and bakeout tests are summarized in Figures 12 and 10. This time the POD for the vibration test was provided by ISL and it is shown in Figure 12. Figure 13 shows the experimental set up of the bakeout test.



7.1.3 RANDOM VIBRATION TEST SPECIFICATION

- *Applicable Standard* ...... : Environmental Levels ISILaunch09, paragraph 4;
- *Test method* ...... : Random Vibration Test at Qualification level;
- *Frequency range* ...... : 20 - 2000 Hz;
- *Vibration level* ...... : 20 Hz // 0.026 g^2/Hz;
  50 Hz // 0.160 g^2/Hz;
  800 Hz // 0.160 g^2/Hz;
  2000 Hz // 0.026 g^2/Hz;
- *Overall level* ...... : 14.1 gRMS;
- *Test Duration* ...... : 60 sec/axis;
- *Test axes* ...... : 03 (X,Y,Z).

7.1.1 RESONANCE SURVEY TEST SPECIFICATION

- *Applicable standard* ...... : Environmental Levels ISILaunch09, paragraph 3;
- *Test method* ...... : Sinusoidal Sweep Test;
- *Frequency range* ...... : 5 - 2000 Hz;
- *Vibration level* ...... : 0,4g_n;
- *Sweep rate* ...... : 2 oct/min;
- *Number of sweep* ...... : 1 (Up-Sweep);
- *Test axes* ...... : 03 (X,Y,Z);

7.1.2 ACCELERATION (QUASI-STATIC) TEST SPECIFICATION

- *Applicable standard* ...... : Environmental Levels ISILaunch09, paragraph 2;
- *Test method* ...... : Sine Burst Test as per NASA Practice No. PT-TE-1420;
- *Excitation frequency* (see NOTE) ...... : 20 Hz;
- *Qualification load* ...... : 18.75g_n;
- *No. of cycles at maximum level* ...... : 5 cycles;
- *No. of cycles for ramp up & down* ... : 4 cycles;
- *Test levels up to full load* ...... : -12 dB; -9 dB; -6 dB, -3 dB & 0 dB;
- *Test axes* ...... : 03 (X,Y,Z).

NOTE: *The selected excitation frequency (20 Hz) is in accordance with the NASA PT-TE-1420 which recommends a value less than 1/3 of the specimen resonance frequency (value identified is between 450 and 500 Hz).*

Figure 12: Vibration requirements for the second qualification campaign.

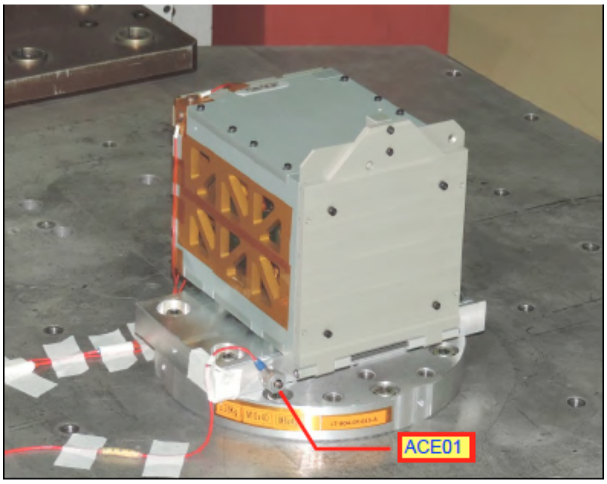


Figure 13: Experimental set up of the vibration test for the second qualification campaign. In this campaign, the POD was provided by ISL.

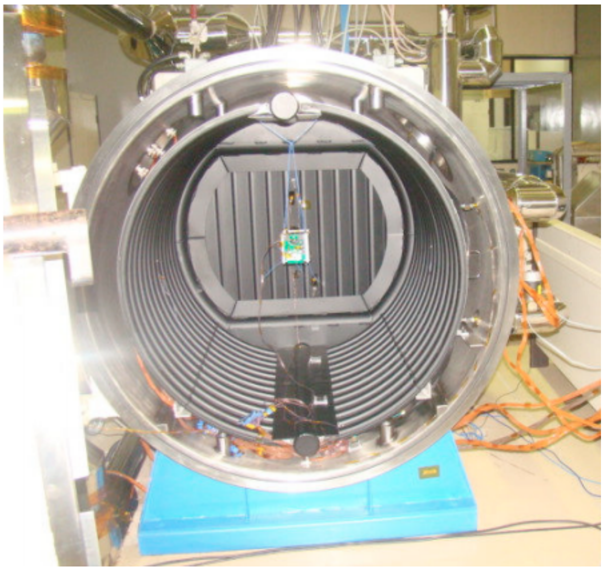


Figure 14: Experimental set up of the bakeout test for the second qualification campaign.

PRELIMINARY RESULTS

After almost a year of operation in space we have some preliminary results that we can summarize in this section. However, we are working on more detailed reports for each of our findings.

The Microchip PIC24 microcontroller has been operating perfectly well in space. Although, the September 2017 solar storm hang out the OBC, a hard reset was enough to make the microcontroller properly operate again.

The temperature sensors in the interior of the satellite shows a kind thermal environment. The measured temperatures go in average from 5 C to 19 C. It is important to notice that temperature sensors are covered with coating, which impact in these measurements.

Ion Lithium battery performs well in space. Degradation is very slow, although preliminary measurements indicates that strong degradation is found after major solar storms. Our preliminary results indicate that this is the case after the September 2017 event.

A sphere, such as the spherical probe of the Langmuir probe, or other reference points together with gyroscopes, knowledge from the solar panels and a simple VGA image (Figure 15) can be combined to provide useful attitude estimation. We are currently evaluating the level of accuracy of our estimation algorithm.

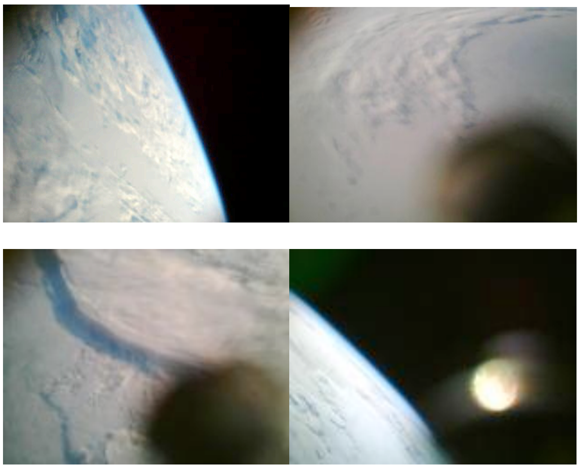


Figure 15: Images taken by SUCHAI in the south pole. The images are taken in the terminators zone for attitude estimation. These images are used in combination with the gyroscopes and with image analysis, since the sun and earth reflection in the Langmuir probe (black sphere) also provides valuable information about the orientation of the spacecraft.

CONCLUSIONS

A CubeSat project was developed at the University of Chile, in a context where the country lacks from a coordinated strategy and support for space endeavors. This type of project showed to be extremely useful to teach professional and teamwork skills in engineering students. The project was also useful to produce highly specialized professionals. It also appears useful to improve the social perception about the feasibility of participating space missions with limited budgets, which is a real concern in developing countries.

Although, starting a satellite project from scratch in a country without much satellite development experience appears as a real disadvantage it also offers some advantages. If the lack of knowledge is seen as a learning opportunity this can be an excellent driver, not only to educate engineers but also if the research rigurosity is used, to train future researchers in the topics. This is more valuable if we recall that Cubeat conditions can be much more challenging to perform similar tasks to those already performed for classical satellites or even for complementary tasks in space. This is extremely important not only for education but also for funding. If knowledge is seeked in rigurose manner then research funding can be obtained, which might guarantee at least in developing countries, some constant source of resources with a civil space program.

Acknowledgments

We would like to acknowledge the great work and compromise of the entire SPEL team, as well as the support of the Faculty of Physical and Mathematical Sciences at the University of Chile.

This work has been partially supported by the grants Fondecyt 1151476, Anillo ACT1405, Fondequip EQM150138 and CONICYT-PCHA/Doctorado Nacional/2016-21161016.

References

1. Harding RC. Space policy in developing countries: the search for security and development on the final frontier, Routledge; 2012.
2. Portilla, José Gregorio. (2012). LA ÓRBITA DEL SATÉLITE LIBERTAD 1. *Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales*, *36*(141), 491-500. Retrieved June 13, 2018, from http://www.scielo.org.co/scielo.php?script=sci_arttext&pid=S0370-39082012000400002&lng=en&tlng=pt.
3. ST/SG/SER.E/792 - Information Furnished in Conformity with the Convention on Registration of Objects Launched into Outer Space. Retrieved June 13, 2018. http://www.unoosa.org/oosa/osoindex/data/documents/pe/st/stsgser.e792.html
4. NanoSatC-Br1. Retrieved June 13, 2018. https://directory.eoportal.org/web/eoportal/satellite-missions/n/nanosatc-br1

5. NASA - NSSDCA. Retrieved June 13, 2018. https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2013-018B

6. ANTELSAT Retrieved June 13, 2018. https://iie.fing.edu.uy/investigacion/grupos/lai/files/ANTELSAT_brochure_2012W01.pdf

7. ST/SG/SER.E/681. Information Furnished in Conformity with the Convention on Registration of Objects Launched into Outer Space. Retrieved June 13, 2018. http://www.unoosa.org/oosa/osoindex/data/documents/ar/st/stsgser.e681.html

8. Diaz, M.A., Zagal, J.C., Falcon, C., Stepanova, M., Valdivia, J.A., Martinez-Ledesma, M., Diaz-Peña, J., Jaramillo, F.R., Romanova, N., Pacheco, E. and Milla, M. “New opportunities offered by Cubesats for space research in Latin America: The SUCHAI project case”. Advances in Space Research, *58*(10), pp.2134-2147, 2016.

9. P. M. Huang, A. G. Darrin and A. A. Knuth, "Agile hardware and software system engineering for innovation," *2012 IEEE Aerospace Conference*, Big Sky, MT, 2012, pp. 1-10.

10. C. Boshuizen, J. Mason, P. Klupar, S. Spanhake, "*Results from the planet labs flock constellation,*" 28th Annual AIAA/USU Conference on Small Satellite, 2014.

11. Gonzalez, C., “Diseño e implementación del software de vuelo para un nano-satélite tipo Cubesat”. Bachelor Thesis at University of Chile, 2013.

12. Opazo, T. “Requerimientos, implementación y verificación del nano-satélite Suchai”. Bachelor Thesis at University of Chile, 2013.

13. Mehrparvar, A. et al. (2014): CubeSat Design Specification Rev. 13. Available at: http://www.wvw.cubesat.org/images/developer/cds_rev13_final2.pdf (last accessed June 13, 2018).

14. Fernandes, G. F., Santos, M. B., Silva, V. D., Almeida, J. S., & Nogueira, P. R. M. (2016). Thermal Tests for CubeSat in Brazil: lessons learned and the challenges for the future. In *67th International Astronautical Congress, Guadalajara, Mexico*.