3Cat-4 Mission, 1-Unit CubeSat for Earth Observation: Evaluation on the qualification and production during Phase D

Albert Morea[1], Lara Fernandez[1], Amadeu Gonga[1], Joan Adrià Ruiz-de-Azua[1], Joan Francesc Muñoz[1], Marc Badia[1], Adrian Perez[1], Alejandro Garcia[1], Ieremia Crisan[1], Luis J. Contreras[1], Marco Sobrino[1], David Llaveria[1] and Adriano Camps[1]

Abstract

The 3Cat-4 mission is a 1-unit CubeSat platform that serves as a technology demonstrator and educational platform for students at Universitat Politècnica de Catalunya (UPC). Promoted by the UPC Nanosatellite and Payload Laboratory (UPC NanoSatLab), the most notable subsystems that innovate in the nanosatellite scenario are (1) the Flexible Microwave Payload - 1 (FMPL-1) [1], a cost-effective payload to execute Global Navigation Satellite System Reflectometry (GNSS-R), and L-band microwave radiometry experiments using a commercial off-the-shelf (COTS) software-defined radio (SDR) and (2) the Nadir Antenna Deployment Subsystem (NADS) [2], an in-orbit deployable high-directivity antenna used by Earth Observation (EO) payloads. This paper presents the findings of the 3Cat-4 mission during Phase D, the qualification and production phase of the project. Since the publication of the first introductory work for this mission in 2019[3], several sections of the subsystems have been redesigned and upgraded to correct previous design flaws or to meet new requirements. In addition, this paper addresses the educational perspective of this mission, analyzing its performance and usefulness in the aforementioned subject.

Keywords

CubeSat, Earth Observation, Phase D, COTS, SDR, Education

[1] UPC NanoSatLab, CommSensLab-UPC, Dept of Signal Theory and Communications, Universitat Politècnica de Catalunya-BarcelonaTech, Spain

Acronyms/Abbreviations

ADCS	*Attitude and Determination Control Subsystem*
AIS	*Automatic Identification System*
AIV	*Assembly, Integration and Verification*
ATC	*Ambient Test Campaign*
COMMS	*Communications Subsystem*
COTS	*Commercial Off the Shelf*
DITL	*Day In The Life*
EO	*Earth Observation*
EPS	*Electric and Power Subsystem*
ESA	*European Space Agency*
ETC	*Environmental Test Campaign*
FFT	*Full Functional Test*
FMPL-1	*Flexible Microwave Payload-1*
GNSS-R	*Global Navigation Satellite System-Reflectometer*
QM	*Qualification Model*
LOS	*Line Of Sight*
MT	*Mission Test*
NADS	*Nadir Antenna Deployment Subsystem*
OBC	*On-board Computer*
SDR	*Software Defined Radio*
TVAC	*Thermal and Vacuum Chamber*
UHF	*Ultra High Frequency*
UPC	*Universitat Politècnica de Catalunya*
ZADS	*Zenit Antenna Deployment Subsystem*

1. Introduction

In the frame of NewSpace, the research centre based in Universitat Politècnica de Catalunya (UPC), Nanosatellite and Payload Laboratory, known as NanoSat Lab, develops CubeSats missions specializing in Earth Observation (EO) payloads. One of these missions is ^{3}Cat-4, a nanosatellite that follows the standard of 1 Unit of envelope. ^{3}Cat-4 develops under the scope of the framework of the ”Fly Your Satellite! II” program of the European Space Agency (ESA) Education Office – ESA Academy.

2. Mission and objectives

The ^{3}Cat-4 mission is a research and educational CubeSat mission based on a 1U standardized envelope. Its main objective is to demonstrate the capabilities of using nanosatellites for challenging Earth Observation (EO) applications.

The satellite is equipped with the in-house developed payload known as Flexible Microwave Payload 1 (FMPL-1). FMPL-1 combines three different instruments in a single board: An Automatic Identification System (AIS) receiver; a L-band radiometer; a Global Navigation System - Reflectometer (GNSS-R). All of them are executed in the same Software Defined Radio (SDR) commercial of the shelf (COTS) component, powered by a Linux operative system.

Regarding the scientific experiments: (1) the Automatic Identification System (AIS) operates in the maritime Very High Frequency (VHF) band (between 30-300 MHz) and enables the wireless exchange of navigation status between vessels. The broadcast messages include the vessel’s name, course, speed and current navigation status. Having this receiver as a pay-load for the mission allows to receive AIS messages from vessels that are far from land, and cannot be collected from the fixed network of AIS receivers. (2) An L-band radiometer is an instrument that receives the radiation emitted by the Earth at L band [3] (1.5 - 2.7 GHz). These measurements can be processed to obtain several environmental parameters such as soil moisture, sea surface salinity, snow density and vegetation optical depth. (3) The GNSS-R technique consists of measuring the direct GNSS signals in their way to the Earth, and also their corresponding reflections on the Earth’s surface [3]. Comparing the variations between both signals, which theoretically are the same, it is possible to infer properties of the reflection surface. Using this technique, it is possible to obtain environmental parameters relevant for research in altimetry, oceanographic wave height and wind speed, cryosphere monitoring and soil moisture.

In terms of educational objectives, the ^{3}Cat-4 mission is conducted entirely at the UPC-NanoSat Lab. The whole team is composed by students from different engineering backgrounds, such as telecommunications, electronics and aerospace engineers, ranging from different educational levels from undergraduates to doctoral students. The main educational objective is to provide a significant experience and knowledge to promote qualified future professionals in the related fields.

2.1. Phase D of the mission

The mission beginnings date back to 2017, when the definition of the proposal was presented and selected by ESA Academy "Fly your Satellite! II" program. Since 2019, the mission entered in the design and implementation of most of the in-house built subsystems. Finally, since early 2021, the mission entered the Phase D to qualify and test the designed subsystems, integrate them, and execute more qualification and testing at a system level.

3. Satellite architecture

The [3]Cat-4 satellite is formed by several subsystems that provide the required power, communications capability and processing capacity. These subsystems are the Electrical and Power Subsystem (EPS), the On-Board Computer (OBC), the Communications Subsystem (COMMS) and finally and linked to COMMS, the Zenith Antenna Deployment Subsystem (ZADS), which provides an Ultra-High Frequency (UHF) Antenna for communications. Then, the payload-oriented subsystems are the FMPL-1, which contains an independent computer, and SDR that executes the EO experiments, and the Nadir Antenna Deployment Subsystem (NADS), which is an in-house developed in-orbit deployment system formed by a 50 centimeters long helix antenna.

In the following figure, an exploited view of the stack is available:

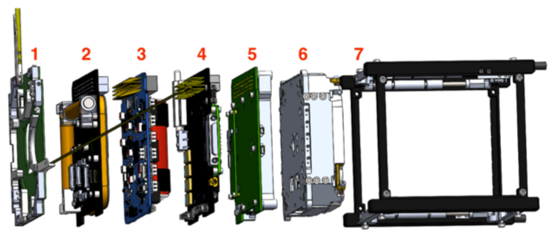

Figure 1. [3]Cat-4 stack exploited view

Starting from the left, there is the top face. The components are stacked as seen in the 3D model, detailing hereunder each number to the component: (1) ZADS, (2) COMMS and ADCS, (3) EPS, (4) OBC, (5) FMPL-1, (6) 1U CubeSat Structure.

In the following figure, a render of the spacecraft with the deployed NADS configuration is available:

Figure 2. [3]Cat-4 configuration with NADS deployed

4. Subsystem level qualification

After the design and validation of the different subsystems that compose the spacecraft, the qualification phase starts. The different subsystems will be separated in two determinant groups: (1) first, the COTS group, meaning that all the components that are COTS are not needed to be tested at subsystem level as their manufacturers and flight heritage certify them. These are the EPS, OBC, ZADS and the mechanical structure; (2) second, the in-house designed and manufactured subsystems, which are needed to be tested to ensure its correct functioning under mission requirements. These are the COMMS, NADS, FMPL-1 and ADCS.

For this reason, the COTS components are not standalone tested or the executed tests are by far less restrictive than in the in-house group. In-house components shall pass a Thermal and Vacuum Chamber test, which tests its operative and non-operative temperature range and a Vibrations test, that ensures the integrity and function of the subsystem under launch conditions.

4.1. Electrical and power subsystem

As a COTS, the GomSpace EPS did not experience a standalone TVAC and Vibrations test. Nonetheless, a different TVAC test was scheduled in order to verify the proper functioning of the battery heaters. Its main intention was to ensure that it was possible to upload a configuration file from the ground segment to the EPS subsystem software, setting the hysteresis temperature that defines the heaters operation range.

Figure 3. EPS subsystem preparation for TVAC testing

4.2. Communications subsystem

As an in-house component, the communications subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

4.3. Zenit Antenna Deployment Subsystem

As a COTS, the ZADS provided by ISISpace did not experience a standalone TVAC and Vibrations test. Nonetheless, strong testing regarding communications has been taken in place, as well as an ambient deployment test to ensure the correct functionality of the deployment subsystem and validate that there are no mechanical stresses when the COTS is mounted on the satellite that prevents it from deploying.

4.4. Nadir Antenna Deployment Subsystem

As an in-house component, the Nadir Antenna Deployment Subsystem has passed an extensive test campaign as a standalone subsystem due to its high complexity and several failure points.

The first test was the Vibrations test, applied to the NADS Qualification Model (QM). In the following figure, a picture of the test is available:

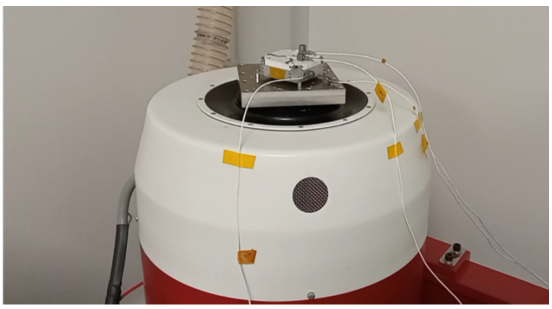

Figure 4. NADS subsystem vibrations test

Then, one of the most significant problems with the NADS deployment was the high current consumption used by the subsystem when burning the wires. For this reason, the system was tested several times in different configurations, being the most relevant critical parameter the cable length that connects the NADS to the rest of the satellite (mainly the stack EPS-OBC).

First, an ambient deployment was attempted, with a successful result, as it can be seen in the following figure:

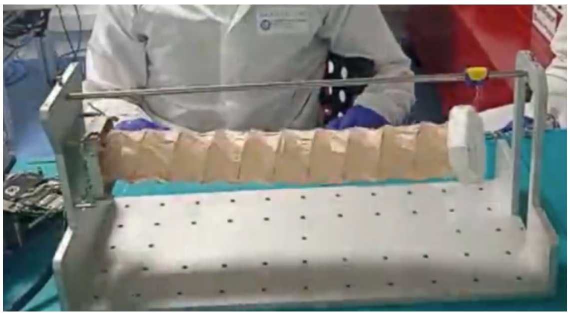

Figure 5. NADS subsystem ambient deployment

Once the ambient deployment attempt was a success, a TVAC deployment was scheduled. In the following figure, a picture of the NADS deployment inside the TVAC can be observed.

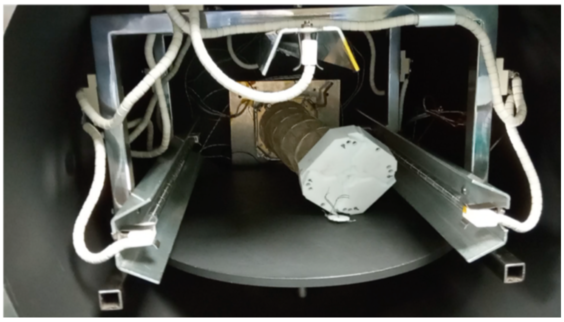

Figure 6. NADS subsystem TVAC deployment

The most relevant outcome of this test is the detection of untrustworthy behavior from deployment switches for temperatures below - 5ºC. This generates a condition for the operation of the mission to only deploy the NADS for temperatures higher than - 5 ºC.

4.5. Flexible Microwave Payload

As an in-house developed component, the communications subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

4.6. Attitude and Determination Control Subsystem

As the ADCS subsystem shares the same board with COMMS, the subsystem has undergone a TVAC test as well as a Vibrations test, successfully passing both of them.

Nonetheless, the last implementation of the ADCS subsystem was the creation of a specific mode that increases the sampling rate of sensor data so as to perform an in-orbit ellipsoid fitting and calibration of the magnetometers. This test mode has been tested in the FlatSat randomly moving the sensors to generate a demand for attitude control by the system.

5. System level qualification

Once the standalone subsystem verification has been executed, the integration must be completed before starting the system level qualification. Figure 7 shows a picture of the spacecraft fully integrated:

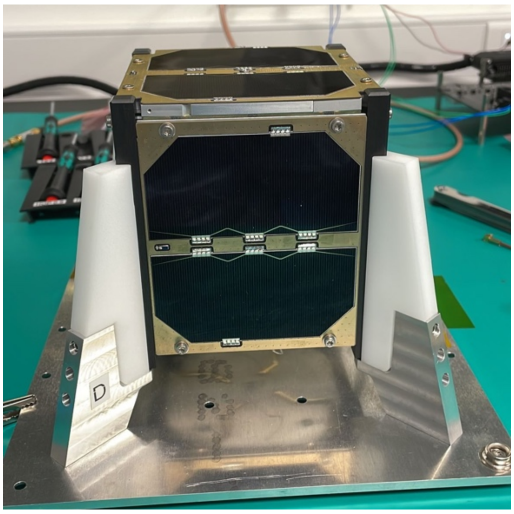

Figure 7. ³Cat-4 completely integrated

Once the system is complete, the system level qualification must take place.

5.1. Ambient Test Campaign

The Ambient Test Campaign (ATC) is a test campaign focused on the validation of the overall spacecraft functionalities and capabilities. It is divided in two different tests:

5.1.1. Full Functional Test

The Full Functional Test (FFT) is a compilation of tests that aims to validate the overall functioning of the spacecraft. It is divided in the Basic Functional Tests, which consists in the simplest requirements needed to be performed by each subsystem as the sending of accurate telemetry and the Mission Oriented Tests, which are more complex functionalities required for the correct development of the mission. In the FFT all the tests are isolated from each other, meaning that the satellite can be powered off between them. No logical time sequence is required to follow, as well as no radio-frequency communications are needed as long as the umbilical cord ones are used through the serial port.

5.1.2. Mission Test

The Mission Test (MT) is the second test of the ATC. Also known as Day In the Life (DITL), this test comprises the same testing executed in FFT but in a scenario that mimics the conditions that the satellite will encounter in orbit. The main intention is to simulate the real operations of the satellite. One of the particularities of this test is that only radiofrequency communications are available as well as Line Of Sight (LOS) between the satellite and the operator are not allowed. Also, both the power and communications regime mimics the real one, with the possibility to only communicate with the satellite for 10 minutes (pass duration) every 90 minutes (orbit) and to apply a sequence of charge/discharge of the satellite's batteries to mimic the real conditions. In order to properly organize and execute this test, at least three roles are needed: Test Operator, who will be the one in charge of the ground segment to operate, the Test Support Operator, a position inside the cleanroom who is monitoring the umbilical debug of the satellite to spot malfunctions and finally the Test Responsible, who is the one in charge of ensuring that the stated constraints are respected and to communicate with both operators and to prevent communications between them.

5.2. Environmental Test Campaign

The Environmental Test Campaign (ETC) is a test campaign focused on the validation and qualification of the spacecraft while recreating real conditions suffered throughout the mission. The ETC is divided in two tests:

5.2.1. Vibrations Test

The vibrations test consists of exposing the spacecraft to different types of vibrations patterns (random, quasistatic and shock) in each of the three axes to validate the correct functioning of the system. The conceptual explanation of this test is that the vibrations used are the ones provided by the launch authority as a minimum profile required to pass in order to launch the satellite with them. A successful vibrations test ensures that the satellite will not suffer during the launch as well as it will not damage any other satellite in the deployer.

5.2.2. TVAC Test

The TVAC test consists of exposing the spacecraft to the ambient conditions that it will suffer while in orbit. Being in orbit affects two main parameters: temperature and pressure. First, temperature can range from – 20 to 60 ºC, depending on the launch orbit and, specifically, on its LTAN. The used values to test the spacecraft at a system level are the qualification values, which are -20 ºC as lower bound and 60 ºC as upper bound. Up to four thermal cycles, which mimic the behavior experienced in orbit, are scheduled and executed to characterize the system response to temperature variations. Nonetheless, these thermal cycles are executed while the ambient pressure is under 10^{-5} mbar, really close to the value experienced in-orbit.

6. Discussion

This work emphasizes the importance of testing, both at subsystem and system level, in order to increase the success rate of our mission. Nonetheless, the future is unpredictable and, although conceptually prediction of possible contingency cases, most of them cannot be tested (specifically at system level) as it is impossible to simulate almost every point of failure of the system, which has several layers of complexity.

7. Conclusions

The main conclusion of this work is that adequate and well-thought test campaigns must be organized at both subsystem and system level to validate the stated requirements. Although, it is important to consider the constraints of each scenario and that a simulation is only a modeling of the future, and modeling is not perfect. Thus, the system must be equipped with recovery procedures in order to cover the potential failures throughout the mission. It is also crucial to train the future satellite operators adequately as they will be the ones who would analyze the telemetry, spot malfunctions and launch recovery protocols.

Acknowledgements

This work has been sponsored by UPC internal funds. The authors are grateful to the ESA staff that created and executed the “ESA Fly your Satellite II”, for the wise advices and willingness to support us in every challenge we have faced.

References

[1] J. F. Munoz-Martin et al., "3Cat-4: Combined GNSS-R, L-Band Radiometer with RFI Mitigation, and AIS Receiver for a I-Unit Cubesat Based on Software Defined Radio," IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium, 2018, pp. 1063-1066, doi: 10.1109/IGARSS.2018.8519037.

[2] Lara Fernandez et al., “Deployment mechanism for a L-band hélix antenna in 1-Unit CubeSat,” Acta Astronautica, 2020. ISSN 0094-5765, doi: 10.1016/j.actaastro.2020.09.005

[3] J. A. Ruiz-de-Azua et al., "3Cat-4 Mission: A 1-Unit CubeSat for Earth Observation with a L-band Radiometer and a GNSS-Reflectometer Using Software Defined Radio," IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, 2019, pp. 8867-8870, doi: 10.1109/IGARSS.2019.8898317.