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Tailoring of ECSS Standard for Space Qualification Test of CubeSat Nano-Satellite

B. Tiseo, V. Quaranta, G. Bruno, G. Sisinni

Abstract**—**There is an increasing demand of nano-satellite development among universities, small companies, and emerging countries. Low-cost and fast-delivery are the main advantages of such class of satellites achieved by the extensive use of commercial-off-the-shelf components. On the other side, the loss of reliability and the poor success rate are limiting the use of nano-satellite to educational and technology demonstration and not to the commercial purpose. Standardization of nano-satellite environmental testing by tailoring the existing test standard for medium/large satellites is then a crucial step for their market growth. Thus, it is fundamental to find the right trade-off between the improvement of reliability and the need to keep their low-cost/fast-delivery advantages. This is particularly even more essential for satellites of CubeSat family. Such miniaturized and standardized satellites have 10 cm cubic form and mass no more than 1.33 kilograms per 1 unit (1U). For this class of nano-satellites, the qualification process is mandatory to reduce the risk of failure during a space mission. This paper reports the description and results of the space qualification test campaign performed on Endurosat's CubeSat nano-satellite and modules. Mechanical and environmental tests have been carried out step by step: from the testing of the single subsystem up to the assembled CubeSat nano-satellite. Functional tests have been performed during all the test campaign to verify the functionalities of the systems. The test duration and levels have been selected by tailoring the European Space Agency standard ECSS-E-ST-10-03C and GEVS: GSFC-STD-7000A.

Keywords**—**CubeSat, Nano-satellite, shock, testing, vibration.

I. INTRODUCTION

CUBESAT are miniaturized and standardized satellites appeared 15 years ago [1]. The first six CubeSats were launched in June 2003 from the Plesetsk Russian launch site with a very low launch cost compared to a typical satellite. Starting form 2018, CubeSats began to venture outside of Earth orbit. Mars Cube One (MarCO) [1]— the first CubeSats to leave Earth — launched on May 5, 2018, along with NASA's InSight lander. InSight is expected to land on Mars on Nov. 26, 2018; it is currently in route and the CubeSats are flying just behind it, as they separated independently from the rocket during launch and are running on solar power [2], [3].

Low-cost and fast-delivery are the main advantages of such class of satellites together with the shorter development time. In addition, compared to a large conventional satellite, a network of several small satellites is potentially more flexible, as it can be reconfigured depending on mission needs. Furthermore, the redundancy of small satellites network also implies lower susceptibility to single-point failure. The QB50 mission demonstrates the possibility of launching a network of CubeSats in the largely unexplored lower thermosphere [4]. CubeSats' advantages, however, are gained by sacrificing reliability against low cost and fast delivery. In fact, several statistics showed the poor success rate of CubeSats .

Bouwmeester et al. [5] showed that only the 50% of nanosatellite (defined by a weight of less than 10 kg) succeeded in mission after the successful launch. Langer et al. [6] made an effort to develop a CubeSat Failure Database and performed a large investigation on CubeSat design and reliability and the development of an estimation tool, as method to reduce the infant mortality based on CubeSat designer's ability to estimate and fitting the necessary tests.

Excellent research carried out by Swartwout [7] showed the causes and the success and failure rates of CubeSat mission and highlighted that more time needs to be devoted to testing after a tailoring process of standards [8]. Test requirements and tailored methods to improve the reliability of nanosatellites are essential to prevent infant mortality and assure mission success in orbit [9], [10]. The qualification process, for this class of satellites, is then mandatory in order to reduce the risk of failure during a space mission [11], [12].

This paper reports description and results of the qualification test campaign performed on Endurosat's CubeSat nano-satellite and modules. CIRA's Space Qualification laboratory has executed physical properties evaluation (weight, center of gravity and momentum of inertia), thermal cycling, thermal vacuum cycling, vibration and shock tests.

The test duration and levels have been selected by tailoring the ESA standard ECSS-E-ST-10-03C [13] and GEVS: GSFC-STD-7000A [14].

II. STATE OF THE ART OF THE CUBESAT FAMILY

Currently, there are more than 1,700 operational satellites orbiting the planet. Compared with 986 in 2011, there has been more than 40% increase in six years. Most of the growth is due to the continued and growing interest in the nano and microsatellites (1-100kg) which are not viewed anymore as a major contributor of space debris in low earth orbit. Nano/micro satellite activities are increasing drastically worldwide with their strong merit of low-cost and quick development. Projections based on public announced launch intentions and future plans of developers and program indicate that between 2,000 and 2,750 nano/microsatellites will be launched in the next five years. Furthermore, although the

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Tiseo B., Quaranta V., and Bruno G. are with the Italian Aerospace Research Center, Capua, 81041 Italy (e-mail: b.tiseo@cira.it, v.quaranta@cira.it, g.bruno@cira.it).

Sisinni G. is with EnduroSat AD, Tundzha Str. 16, 1606 Sofia, Bulgaria (e-mail: sisinni@endurosat.com).

civil sector remains strong, the commercial sector will contribute over 70% of total amount of small satellite launched.

Currently, most of the small spacecraft launched are part of a specific class of nanosatellite called CubeSats. They are miniaturized and standardized satellites consisting of a multiple of 10 cm cubic form units and mass of no more than 1.33 kilograms per unit. Due to the lower development costs and shorter development time, commercial applications of CubeSats are rapidly growing providing an attractive solution for on-orbit verification of challenging space missions and technologies.

The CubeSat appeared 15 years ago as a project of the California Polytechnic State University (Cal Poly) and Stanford University to facilitate the access to space to universities worldwide performing space science and exploration. These universities in 1999 developed the CubeSat Design Specification which is still the standard used by the developers of this satellite. This standard contains requirements that mainly facilitate the integration and the launch processes regulating aspects such as dimensions and mounting procedures. Guidelines for System's design, interface requirement is not covered by this standard.

CubeSats consist of the same number of subsystems of a medium or large satellite. All the subsystems are responsible of specific tasks which are vital for the proper functioning of the entire system. They can be summarized as follows:

- Structure and mechanism
- Power
- On-board data handling
- Communication
- Thermal control
- Attitude determination and control system (ADCS)
- Propulsion

The subsystems define the infrastructure of the spacecraft, namely bus. The payload, which represents the purpose of the mission, drives the design requirements of the bus. Following a brief description of each of them is presented.

A. Structure

The main role of the structure is to support all the components of the spacecraft and create location for the payload. It has to sustain the loads and vibrations experienced during the launch, separation of the stages and deployment of solar panels, antennas or any other mechanisms.

In addition, the structure represents the mechanical interfaces between the satellite and the launcher, which means that it has to be designed, not only according to the spacecraft design requirements, but also considering the specific launch vehicle. This is especially true for CubeSats since they have to meet the external dimensions and shape requirements of the dispensers from which they are deployed.

Depending on the specific mission, structures are used also for thermal management, radiation shielding, and physical connection with mechanism.

Within smallsats, the most used materials are aluminum alloys, which guarantee mechanical material stability in vacuum, mechanical stiffness and lightness.

B. Power

The electric power subsystem generates, controls, stores, and distributes electrical current through all the systems of the spacecraft. Usually it features three components: solar arrays as power source, batteries as power storage and the power station for control and distribution.

A power budget analysis should be performed to design and size all the components of this system. This analysis takes in consideration all the parameters of the mission: power consumption of each module, orbit altitude, sun-angle condition, mission life cycles and so on in order to have always a positive power budget. This means that the power available per orbit is more than the power consumption of the spacecraft.

Because of the small available surface area of nano and micro satellite, if fixed solar panels are used, the available power can be relatively small. Therefore, deployable solar panels are available even for CubeSat platform with the capability of rotation mechanism to fix the position of the solar panels towards the sunlight.

Current state-of-the-art solar cells used in small satellite are triple junction cells which can convert solar radiation in electricity with efficiency between 28% and 33%.

In order to provide a constant source of electric power, batteries are used when the satellite is not in direct sunlight. The most used batteries in small satellites are nickel-cadmium (NiCd), nickel-hydrogen ($NiH2$), lithium-ion (Li-ion) and lithium polymer (Li-po). Most CubeSats today use Lithium Ion and Lithium Polymer technologies due to their high energy density. To maximize the efficiency of the battery, their temperature has to be kept under specific values. For this reason, heaters are used when the temperature goes below a certain level (0-5 °C). In addition, to avoid high temperature, which can cause explosion of the batteries, radiators are used for heating transfer.

The electrical power system controls and distributes the power through the spacecraft subsystems and instruments protecting batteries and systems from non-nominal current and voltage. Commonly, EPS for small satellites have 3.3 V and 5 V power buses.

C. Onboard and Data Handling

On-board data handling system controls the handling and the storage of satellite's health data and all the data generated by the payload. Currently, most nanosatellites are based on Advanced RISC Machines (ARMs) processors because of their low power consumption and high performance computational capabilities. Concerning memory technologies, flash memory chips are widely used because the total memory can easily reach several GB.

Current data handling systems make use of several interfaces such us Serial, I2C, SPI, USB and so on to interface devices and controllers. I2C protocol is commonly used in most nano-satellites because of its high flexibility and reconfigurability and its low power consumption. On the other hand, the main disadvantage is the low stability and sensitivity to EMI.

D.Communication

The communication subsystem assures the communication between the satellite and ground in both up-link and down-link directions. Mainly, it is divided in:

1) Telemetry, Tracking & Control (TT&C) which provides central communication and control, collecting and transmitting vital data and health status information between the spacecraft and the ground.
2) Payload mission Data downlink to transmit the data of the payload onboard the spacecraft to the ground.

The communications subsystems consist of receivers, transmitters, transceivers (receiver and transmitter in the same module) and antennas that can be deployed and oriented and pointed to the ground station using mechanism or controlling the attitude of the entire spacecraft.

For TT&C communication system in small satellite, UHF and VHF frequency bands are used with deployable rod/whip antenna due to the low data rates required especially in uplink. On the other hand, new mission applications such as remote sensing which generate large amount of data that have to be downloaded on the ground lead to focus the development in improving downlink data rates. For this reason, S-band, X-band, and Ka-band communication system with high gain antennas (patch antennas or deployable dish) are utilized when higher data rates are required. New miniaturized S-band transmitter targets to reach over 50 Mbps downlink data rate; X-band transmitter demonstrated to achieve over 220 Mbps. The drawback of using such systems in small platform is the higher power consumption and more strict requirements on the attitude control of the spacecraft.

Lately, also Software Defined Radio (SDR) are used in small platform because of the flexibility in terms of operating frequencies and modulation. Here again, the main disadvantage is the high-power consumption.

E. Attitude Determination & Control System

The Attitude Determination & Control System (ADCS) aims to direct the satellite into a desired direction and allows the satellite to remain stabilized and pointed correctly.

Mainly, an ADCS features:

1) An array of sensors such as sun sensors, star tracker, accelerometers, MEMS gyros and magnetometers which give information about the attitude and attitude rate of the satellite;
2) Actuators such as magnetorquers, reaction wheels and thruster to change and control the attitude of the spacecraft.

In small satellite platforms, fully integrated ADCS subsystems are used to provide 3-axis stabilization with pointing accuracy better than 0.1°. Available low cost ADCS for CubeSat can fit a volume less than 0.3U and mass less than 300 g providing coarse pointing capability with accuracy of less than 5°.

A Global Navigation Satellite System, GNSS receiver are used for navigation and guidance performing orbit determination. Miniaturized GNSS receivers with mass less than 50 g and accuracy of 1.5 m are widely used also in CubeSat platform.

F. Thermal

The thermal system regulates the temperature of the satellite's components maintaining it within specific range. Mostly, in small satellite platform, the thermal control of the satellite uses passive systems such as radiators, coatings, tapes and so on. Usage of specific materials and mechanical interfaces of the components will allow transferring the heat loads to the external structure. In most cases, small heaters can be used to avoid low temperature of the battery packs, which will prematurely end their useful life.

G.Propulsion

Miniaturized propulsion systems have been developed recently in order to provide orbital station keeping, attitude control, maneuvers capability in small buses. Chemical propulsion allows high thrust impulsive maneuver and low specific impulse. On the contrary, electric propulsion with their high specific impulse allows achieving high accelerations for interplanetary mission.

III. NANO-SATELLITE ENVIRONMENTAL TESTING

A drawback of the nano-satellites and CubeSats has been limited reliability. In order to promote the commercial application, there is an urgent need to improve their reliability while keeping their advantages, low-cost and fast delivery. International initiatives, to standardize test requirements and test methods prior to the launch, to qualify the design and manufacturing method of small-scale satellites are fundamental for cost effective growth of Nanosatellite and other canisterized satellites.

According to the standard, CubeSats have to meet the launch provider requirements to ensure the safety of the launching system itself. In the case the launcher is unknown, the standard recommends using The General Environmental Verification Standard (GEVS, GSFC-STD-7000) and MIL-STD-1540 as guidelines.

In general, such testing standards, e.g. GEVS - GSFC-STD-7000 or ECSS-E-ST-10-03C were developed for medium and large satellites in which high reliability in space is needed. Due to the very small satellite class, low procurement cost, short development, extensive use of non space-qualified commercial-off the shelf (COTS) part and components, the testing process shall be tailored to reflect the reduced complexity of these projects. Nevertheless, the success of the mission is guaranteed only by implementing good engineering practice, testing and verification of the systems even if they are used in small satellite platforms. At the minimum level, random vibration, thermal vacuum bake-out and shock test will be performed to all CubeSats.

A campaign of test at qualification program on the engineering models will ensure that the unit will be capable of surviving the mechanical loads experiences during the launch phase and the harsh space environmental conditions.

Acceptance test will be performed on the flight model (the unit that will actually fly) and they are characterized by lower levels and durations of the tests compared to the qualification ones. These tests are performed usually prior to the launch in order to be compliant also with the test requirements of the launch provider.

Mechanical tests are performed in order to demonstrate that the systems are able to survive the vibrations and loads experienced throughout launch and deployment with the launcher. In order to satisfy and meet the requirements of most of the launch vehicle, the General Environmental Verification Standard (GEVS, GSFC-STD-7000) should be used to define test levels and conditions.

Environmental tests will demonstrate that the system can survive the thermal and pressure conditions experienced in the space environment. ECSS-E-ST-10-03C standard can be used to derive test requirements and conditions.

A list of high-level functional test shall be developed for validation. Functionality of the systems shall be verified after each test in order to verify that the test itself do not modify the performances and functionalities. Functional tests are performed during the thermal cycling and thermal vacuum cycling to check the system in that specific environmental conditions.

Electromagnetic compatibility (EMC) tests are not always performed for such class of satellites but they will ensure that each system does not introduce electromagnetic disturbances (known as radiated and conducted emissions) and that it continues to function as intended in in its electromagnetic environment. The standard ECSS-E-ST-20-07C can be used to define procedures and conditions. Test level strictly depends on the mission profile and on the other systems on board.

IV. ENDUROSAT CUBESAT QUALIFICATION TEST

The space qualification test campaign has been the final phase of the EnduroSat CubeSat development.

EnduroSat CubeSat and subsystems underwent an extensive qualification test campaign to demonstrate that the engineering qualification models are able to survive:

1) The mechanical stresses experienced throughout launch and deployment with an undefined launcher;
2) The thermal and pressure conditions experienced in the space environment.

Qualification test levels and duration followed the ESA standard ECSS-E-ST-10-03C and GEVS: GSFC-STD-7000A.

The test sequence is reported in Fig. 1.

The activity started with the CubeSat physical properties measurements. Center of Gravity- CoG and Moment of Inertia -MoI are crucial to the correct functioning of small satellite attitude control systems and as a consequence, center of mass and moment of inertia measurements are an important step in the final verification of a CubeSat. The mass properties have been evaluated along all three directions by positioning the CubeSat and modules on the plate of the Space Electronics instrument, model SE90168, Fig. 2. With reference to the coordinate system origins showed in Fig. 2 and 3 (b), test results reported in Table I. Also, the moment of inertia has been calculated for each principal direction. To measure the MOI, the CubeSat has been positioned on the plate of Space Electronics MOI measurement system, as shown in Fig. 3. Test results are reported in Table II.

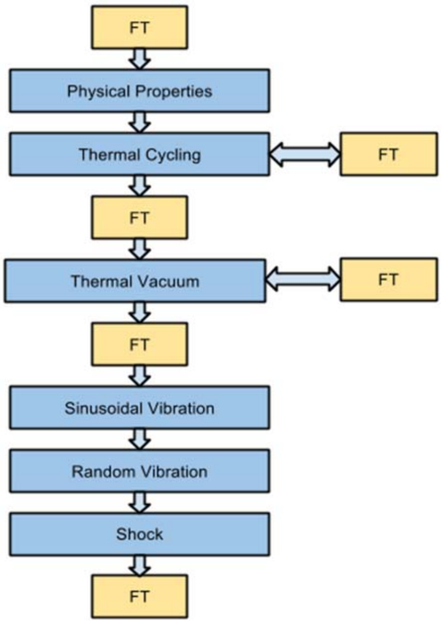

Fig. 1 EnduroSat CubeSat and Subsystems Qualification test sequence

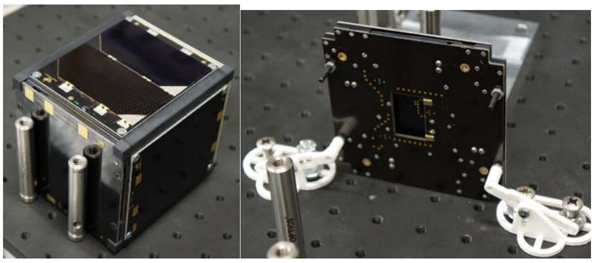

Fig. 2 CubeSat and modules on instrument plate for CoG measurement

TABLE I
CUBESAT COG MEASUREMENT

Measure Direction	CoG Coordinate (X; Y)
x axis	(67.55; 55.15) [mm]
y axis	(66.15; 54.35) [mm]
z axis	(53.95; 55.85) [mm]

TABLE II
CUBESAT MOI MEASUREMENT

Measurement Direction	MOI Value
x axis	17.64 [kg*cm^2]
y axis	19.15 [kg*cm^2]
z axis	16.61 [kg*cm^2]

(a) (b)

Fig. 3 (a) CUBESAT mounted on Space Electronics MOI XR 250 (b) Focus on Z axis installation

In order to verify the CubeSat performance in extreme temperatures conditions and in case, to identify initial defect, thermal cycling test has been carried out in atmospheric pressure by using the ATT- Angelantoni climatic chamber CH 2000.

All systems have been placed on Teflon sheet, which provides thermal insulation between test articles and base plate of the chamber, as shown in Fig. 4. Pt100 sensors have been used to measure temperature on CubeSat and modules. All sensors and cables have been fixed by using Kapton tape. Systems have been exposed to four cycles between extreme temperatures of -20 °C and 60 °C, applying a dwell time of 2 hours, as shown in Fig. 5. Functional check has not shown any problems, before, during and after test.

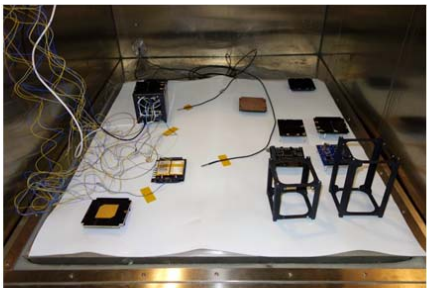

Fig. 4 CubeSat and modules in the climatic ATT Climatic chamber CH 2000

CubeSat and modules also underwent thermal vacuum test in order to qualify their operation when they are exposed to a vacuum and temperature variation imposed by the space environment. The test has been performed by using the ATT-Angelantoni HVT 2000 thermal vacuum chamber **Hata! Başvuru kaynağı bulunamadı.** (a).

All systems have been placed on Teflon small bricks, which provides thermal insulation between test articles and base plate of the chamber, as shown in **Hata! Başvuru kaynağı bulunamadı.** (b). CubeSat and modules have been exposed in high vacuum conditions (pressure < 10^{-6} mbar) to four cycles between extreme temperature of -20 °C and 60 °C, applying a dwell time of 2 hours, as shown in Fig. 7. Temperatures sensors have been located on the main interest positions as reported in Table III. All functionality (Solar Panel, Battery and EPS) have been tested during test.

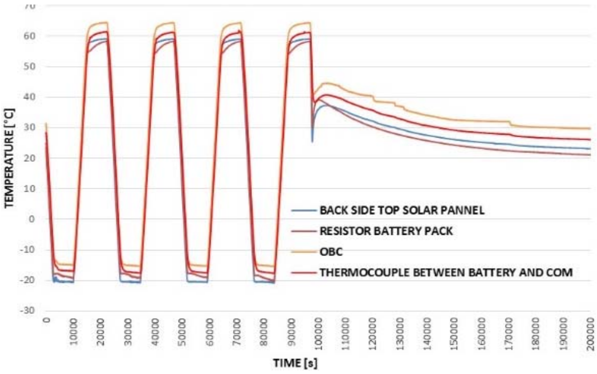

Fig. 5 Thermal Cycling Test-Temperature vs Time

Fig. 6 (a) HVT 2000 TVC

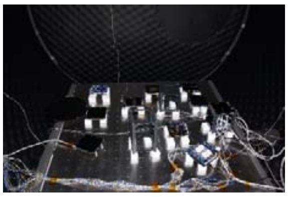

Fig. 6 (b) Systems installed in TVC

TABLE IIIII
TVC TEST - TEMPERATURE SENSORS POSITION

ID temperature sensor	Position
38B6	Cold plate, middle
SS2C	Shroud bottom side
SS1D	Antenna UHF
SS1B	Battery charge regulator (EPS)
SS2B	3.3V bus (EPS)
SS1C	Solar panel – dc/dc converter
SS1F	V bus (EPS)
SS1A	Resistor battery pack (EPS)
SS1E	On board computer
SS2A	Between EPS and COMM

After thermal test, CubeSat and modules underwent vibration and shock test on all three axes.

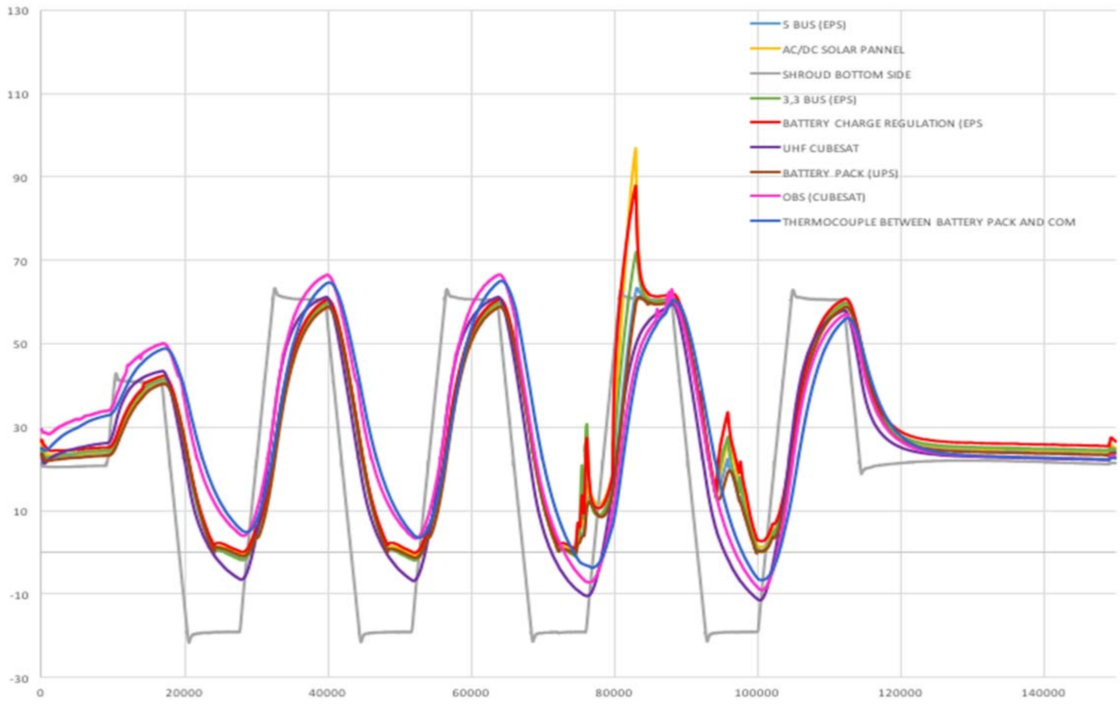

Fig. 7 Thermal Vacuum Test-Temperature vs Time

Vibrational tests have been executed by using the shaker TIRA S597LS-440 controlled by the Vibration Research control Acquisition System, in turn managed by the Vibration View software. A dedicated mechanical fixture has been used to connect P-POD and modules on the vibrating table, as shown in Fig. 8. One PCB accelerometer model 365A16, has been used as feedback control accelerometer.

Fig. 8 CubeSat and modules installed on TIRA Shaker

Sinusoidal vibration with a sweep rate of 2 Oct/min and repetition of three for each axis has been executed according to test levels reported in Tables IV and shown in Fig. 9.

Random vibration levels are reported in Table V and showed in Fig. 10.

TABLE IV
SINE VIBRATION TEST - AMPLITUDE VS. FREQUENCY

Frequency [Hz]	Amplitude [g]
5 – 100	2.5
100 - 140	1.25

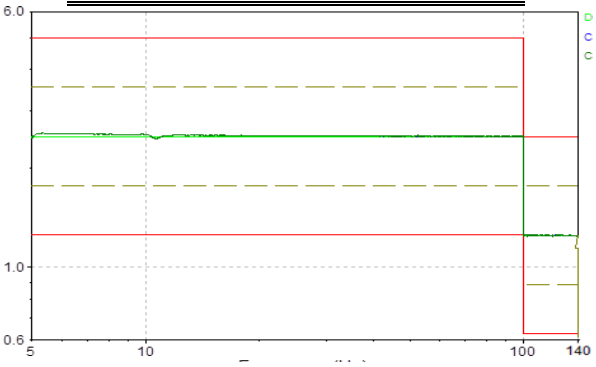

Fig. 9 Sine vibration –Acceleration (G) vs time (sec)

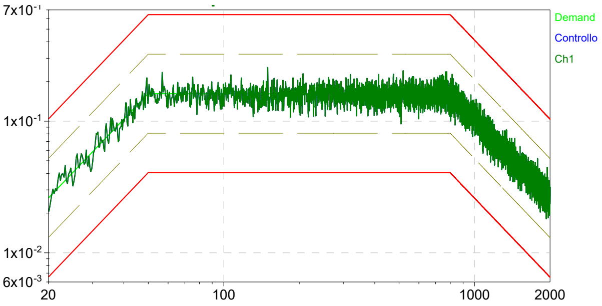

Fig. 10 Random Vibration –ASD (G^2/Hz) vs Frequency

Shock Tests have been performed by using a mechanical facility, designed by CIRA. It is made of a frame of modular aluminum profiles supporting a resonant plate and hosting an hammer with its arm. The hammer can be moved with an electromechanical motor between two positions as shown in Fig. 11: in-plane and out-of-plane configurations. A pneumatic brake is used as safety mechanism to maintain the hammer in its position before the unfastening (obtained by means of a fast hook device manually controlled by the operator). A rotary encoder connected to a laptop is used to measure the angle of the hammer arm with the horizontal plane (with a precision of about 0.1°).

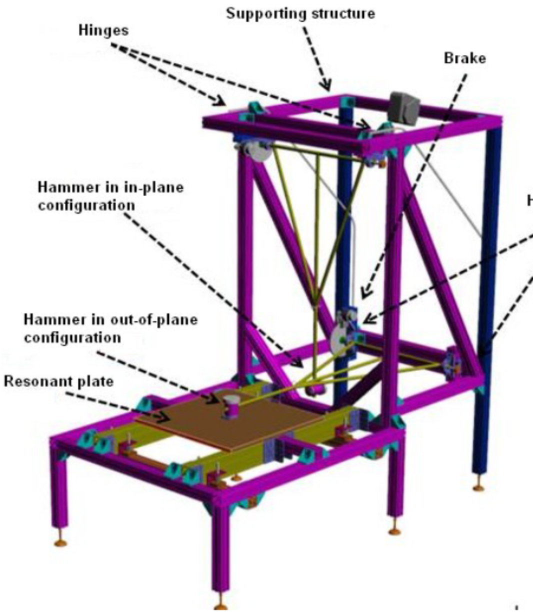

Fig. 11 CIRA Shock Test Facility Sketch

TABLE V
RANDOM VIBRATION TEST - ASD VS. FREQUENCY

Frequency [Hz]	ASD level [g^2/Hz]
20	0.026
20 – 50	+6 dB/oct
50 – 800	0.16
800 – 2000	-6 dB/oct
2000	0.026
Overall	14.1 G_{rms}

For shock test, CubeSat and modules has been mounted throughout two mechanical fixtures to the resonant plate of CIRA shock test facility. In particular, for horizontal excitation (X, Y), a “L” shaped aluminium plate has been bolted on the resonant plate; while for vertical excitation (Z), a flat mechanical aluminium plate, has been used as shown in Fig. 12 Fig. 13.

Shock Response Spectrum is reported in Table VI.

The test has started with a tuning phase in order to evaluate the effects of the combination of several parameters (hammer impact velocity, hammer mass) on the obtained SRS. The tuning phase has been performed on a dummy test item, matching the mass and inertia properties of the actual CubeSat. Once identified the best parameters combination allowing the requested SRS achievement, the shock test has been executed, Fig. 14.

Functional test fulfilled after all test campaign has not showed up mechanical failure or software malfunctioning.

TABLE VI
SRS - SHOCK RESPONSE SPECTRUM

FREQUENCY (HZ)	SRS (G)
30	5
100	100
700	1500
1000	2400
1500	4000
5000	4000
10000	2000

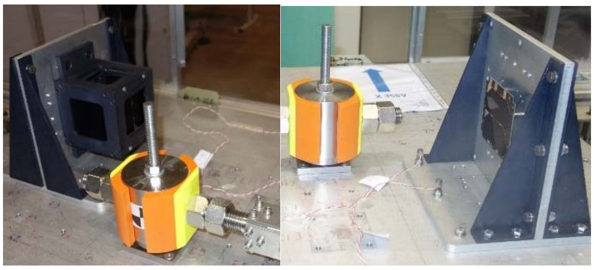

Fig. 12 CubeSat and modules installed on ringing plate of shock facility. Horizontal axis

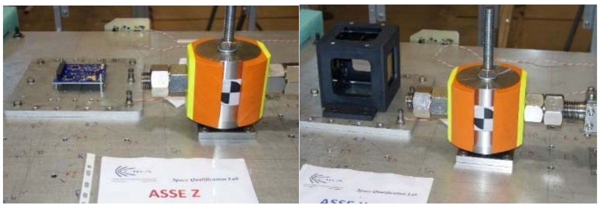

Fig. 13 CubeSat and modules installed on ringing plate of shock facility. Vertical axis

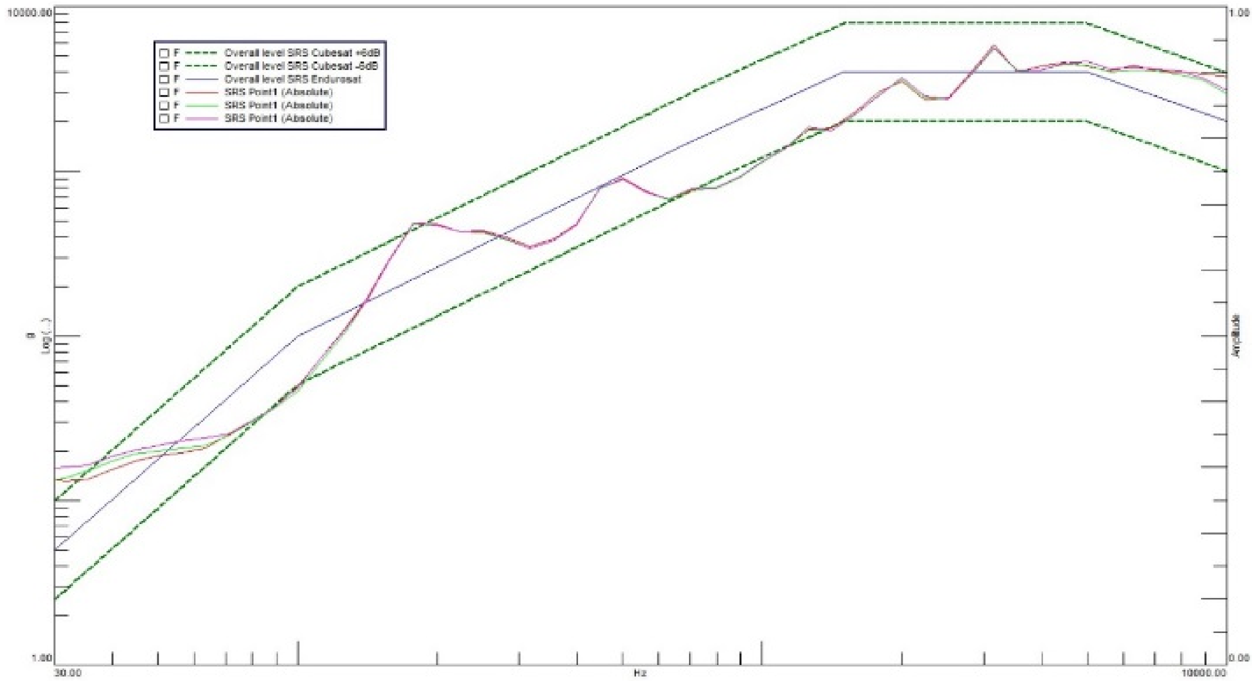

Fig. 14 CubeSat SRS vs Frequency along X Axis

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