THE BUGS EXPERIMENT: OVERVIEW AND IN-FLIGHT RESULTS

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ABSTRACT

Boom for University Gravity-gradient stabilized Satellite (BUGS) is a student experiment proposed by the *Space Robotics Laboratory* (SRL) of the II Faculty of Engineering of the University of Bologna Alma Mater Studiorum in cooperation with the School of Aerospace Engineering of the Sapienza, University of Roma. The BUGS experiment was selected to fly on board the sounding rocket REXUS-7 and it has two main goals: the hands-on education and the deployment test, in near microgravity conditions, of a boom for gravity gradient attitude stabilization of small satellites. The educational purpose consists on providing the university students with the opportunity of a practical experience in a real space project during their master and PhD courses. During the whole experiment lifecycle, starting from the experiment selection until the launch campaign and post-flight data analysis, the students are involved in all phases of the project: they analyze the problems, propose solutions and test them. Moreover, they have the opportunity to meet experts coming from different European space agencies and to present the achieved results. The proposed boom is based on an innovative design, exploiting rigidity properties of tape coiled springs. Two boom prototypes, one longer (3 m in deployed configuration) and one shorter (2 m in deployed configuration), were tested on board REXUS-7 with the aim to achieve data related to their dynamic behavior in orbit. These booms were developed by students of the *Space Robotics Laboratory* of the II Faculty of Engineering of the University of Bologna.

Another technological objective of the BUGS experiment was testing the thermal cutter system for boom deployment and the ejection system.

The paper gives a general overview of the experiment showing the students participation to the training activities, the experiment design, building and flight. The data analysis and results are also summarized in the paper.

1. INTRODUCTION

The BUGS experiment is a student-built experiment developed to fly on board the sounding rocket REXUS-7 (Rocket-borne EXperiments for University Students) with the sponsorship of the ESA's (European Space Agency) Education Office, which supports the participation of European students to the REXUS/BEXUS Programme (Rocket and Balloon Experiments for University Students), on the basis of a call for proposals and experiments selection. The indicative timetable for the experiments is 18 months from the call for proposals.

REXUS is conducted by EuroLaunch, a co-operative agreement between the Swedish Space Corporation (SSC) and the German Aerospace Center (DLR), Mobile Rocket Base (MORABA) in the area of suborbital services for sounding rocket launches and stratospheric balloon flights [1]. REXUS is financed by the Swedish National Space Board (SNSB) and the German Aerospace Center (DLR) [1].

A view of REXUS-7 with the integrated experiment modules during the pre-launch phase at the Esrange Space Center, near Kiruna in northern Sweden, is given in Fig.1. In this picture it is possible to see the experiments arrangement and the BUGS position.

There is a module for each student experiment: this modularised configuration provides simple interfaces, good flexibility and independence between experiment modules [1].

REXUS-7 was launched on 2th of March 2010 at 8.25 local time carrying three student experiments onboard. The rocket reached an altitude of 83 km and landed north of Esrange Space Center.

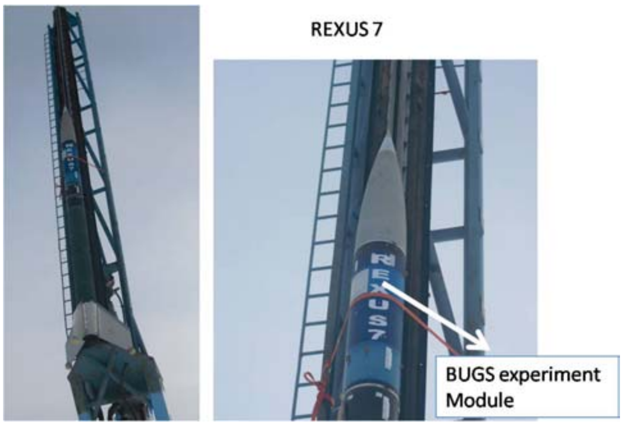

Figure 1 – REXUS-7 in the pre-launch configuration

The BUGS experiment, born from an idea of the researchers of the *Space Robotics Laboratory* (SRL) of the II Faculty of Engineering of the University of Bologna Alma Mater Studiorum, was proposed and developed in cooperation with the Sapienza, University of Roma.

1.1. Experiment objectives

The main objectives of the BUGS experiments are the boom prototype deployment test in near microgravity conditions and the hands-on education of university students.

In order to use the boom on board of a satellite, it is important to calculate how the damping system should work to reduce properly the vibrations caused by the boom deployment. This kind of test can not be performed on the ground, because the absence of the microgravity condition and of the atmosphere do not allow the observation of this effect.

Technological objectives can be summarized in following points:

- boom deployment test in space-flight conditions (near microgravity conditions);
- to try to estimate boom damping time and boom modal frequencies;
- to evaluate the reaction of the satellite-body due to the boom deployment in orbit;
- to qualify the boom for small and low cost satellite class;
- to qualify the thermal cutter and the ejection system.

The proposed boom prototype is based on an innovative, low cost concept, which uses the principle of the tape coil spring, Fig. 2; it can be deployed once and it maintains its rigidity since every coil is blocked inside the following one [2]. For the first time this coil spring has been used to develop an experiment named SIRDARIA (Spacecraft Integrated Re-entry Device, Aero-Resistant Increasing Area), hosted on board UNISAT-4 microsatellite [3].

Figure 2 – Tape coil spring employed for boom prototype development.

The first manufactured boom prototype was 15 cm long in stowed configuration and 3 m long in the deployed configuration [4]; weight is about 700 g. The second manufactured boom prototype (for the BUGS experiment) is 17 cm long in stowed configuration, 3 m long in the deployed configuration and its diameter is 5 cm. After, a shorter boom prototype was developed. This second boom is a back-up unit; its diameter is 3.5 cm and it is 2 m long in the deployed configuration. Both booms have been assembled and qualified to fly with the BUGS experiment on board REXUS rocket, Fig. 3.

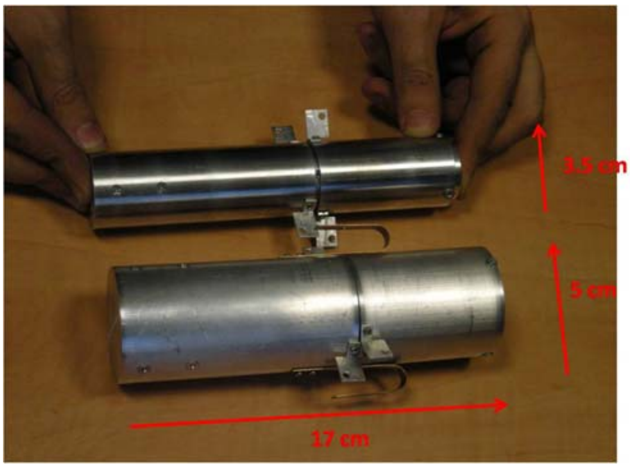

Figure 3 – Booms prototype mock-up

Among the educational activities and objectives there are:

- team work and team building;
- problem solving;
- possibility to work in an international context and to meet experts coming from main European Space Agency;
- comparison and cooperation with other student teams;
- practice with ESA's procedures and knowledge of ECSS standards;
- papers presentation and student participation to symposiums, workshops, conferences.

2. EXPERIMENT DESCRIPTION

2.1. Mechanical design and configuration

The experiment configuration is based on the boom prototype, the thermal cut system for the boom deployment, the ejection system required to separate the boom before the parachute opening and a camera for the boom behavior monitoring. The system is redundant: there are two booms, two cameras and a double ejection system. A view of the BUGS experiment manufactured and integrated in the REXUS cylindrical experiment module, during the bench tests performed at DLR, is visible in the following Fig. 4.

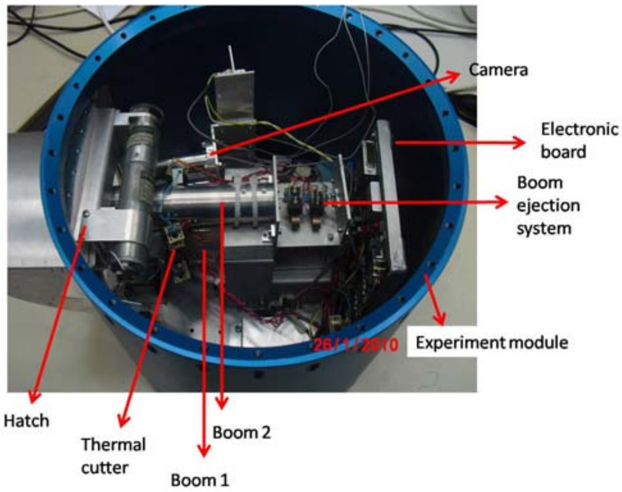

Figure 4 – BUGS experiment overview

The small boom is placed above the big one; each one of them has its proper thermal cutters, both for deployment and for ejection. An omega in Aluminum helps to fix the larger boom to the structure, while the smallest one is blocked to its base with bands. The cameras are fixed directly on the experiment module and integrated in a mechanical modularized support in order to change easily the camera position and orientation during the tests and the system integration.

The first camera uses the REXUS TV downlink channel; the second camera data are recorded in a small data recorder. This minimal configuration has been selected in order to simplify electronics required for the experiment and to improve system reliability. The idea is to use small cameras which do not require a computer for data management and which start working and recording data when the power supply is active.
All selected components are commercial: in this way it was possible to reduce the procurement phase time and to manufacture them in a small laboratory reducing also costs and realization times.

The electronic board is hosted is hosted in a 3 mm thick Aluminum box, treated with pressurized water and glass powder to increase its rigidity and manufactured with the support of the ESA's mechanical laboratories. The box is placed vertically behind the main structure (Fig. 4).

2.2. Experiment process flow

The experiment process flow is available in Fig. 6. The primary objective of this experiment is the deployment test of boom prototypes in space-flight conditions in order to understand and to evaluate boom dynamic behaviour. Boom must be deployed when REXUS has reached the microgravity conditions and it must be ejected before the parachute opening. Power and signals to switch on BUGS experiment are provided by REXUS service module (RXSM). BUGS electronics is connected to the REXUS power supply via voltage regulators (RXSM Voltage 28 V).

The experiment use two signals to control the events sequence [1]. The SODS signal [1] at T0+120s will command the boom deployment: the rocket is about 30 seconds far from the apogee (as estimated by DLR experts), so microgravity condition would have been reached. The thermal cutter lets the boom deploy (SOE+1 sec, Fig. 5, [1, 2]), and the experiment starts. The SOE signal at T0+45s commands the ejection of the first boom. The second boom is deployed at SOE+65s and it is ejected at SOE+110s (Fig. 5).

The Time Events based on the predicted flight trajectory is the following for the BUGS experiment is given in Table 1 [5].

Time [s]	Event
T+0	Lift Off
T+0	BUGS camera on
T+100	BUGS Hatch Power
T+106	BUGS Boom 1 deployment
T+144.4	Apogee
T+150	BUGS Boom 1 Ejection (+45s)
T+170	BUGS Boom 2 deployment
T+215	BUGS Boom 2 ejection
T+230	BUGS Hatch SOE
T+258.4	Maximum deceleration (26 km)
T+600	Power Off for experiments

Table 1 – BUGS Time Events

The REXUS recovery system is designed to decelerate the velocity to 8 m/s at the impact time (about 358 sec after the ignition [1]). After the landing, the experiment modules are recovered by helicopter within a few hours.

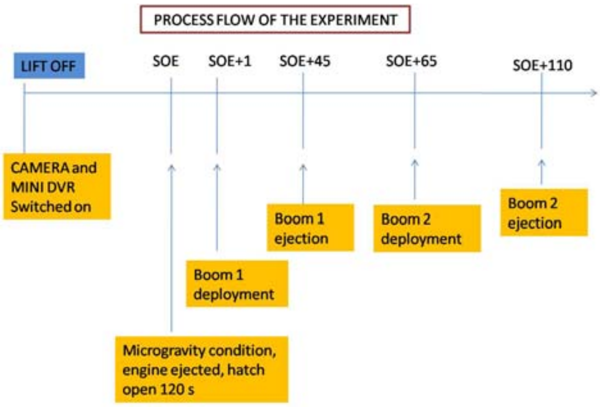

Figure 5 – BUGS experiment process flow

3. ENVIRONMENTAL TESTS

3.1. Thermal test

Preliminary thermal test of the boom prototype was performed (Fig. 6) in order to verify the nominal boom behaviour in high temperature conditions [2]. The test was performed at DMA Marchiori srl in Aprilia near Rome. Two thermal sensors were employed to measure local temperature on sensible elements as the Aluminium support with the hatch where is located the dynema line and the bottom part of the boom where the interface with the electronic box is arranged.

The main goals were to evaluate the boom material (specially springs) behaviour in high temperature conditions and to estimate if there is the possibility to cut accidentally the dynema line when the Aluminium support reaches high temperatures. Tests were performed in a thermal camera operating with the inner environmental temperature in the range 60°C-100°C (pressure 1 atm).

Figure 6 - Thermal camera with two temperature sensors to measure boom local parts

Test duration was fixed to 10 minutes to be conservative. Sensor 1 located on the Aluminium support for dynema line reached 86 °C, whereas sensor 2 located between the Aluminium plate and the boom in the bottom part reached 79.5°C. The deployment test was performed in the worst conditions after the thermal test, it means when the boom reached the maximum temperature after 10 minutes (86.5°C). Deployment test in this condition was performed successfully.

3.2. Vibration test

Vibration test was performed successfully at the Mechanical System Laboratory of ESA-ESTEC with the sponsorship of the ESA's Educational Office, Fig. 7. Requirements were fixed according to REXUS User Manual [1]. According with Eurolaunch vibration tests have been performed only on the Z axis for the experiment acceptance. Random qualification test lasted 60 seconds at 6.0 grms. The shaker vibrations is monitored by accelerometers. The accelerometers provide a feedback signal to the control computer.

Figure 7 – BUGS experiment vibration test at the ESTEC/ESA

From the comparison of the spectra achieved by the test accelerometer before (Fig. 8) and after (Fig. 9) the random vibration, it can be noticed that the resonant frequencies did not change significantly. Thus can be stated that no parts reduced their rigidity during random vibration tests simulating launch phase and the experiment can be considered qualified to be boarded on REXUS launcher.

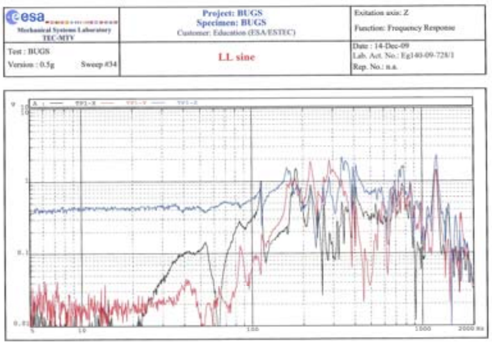

Figure 8 – Test accelerometer, pre-random sinusoidal sweep

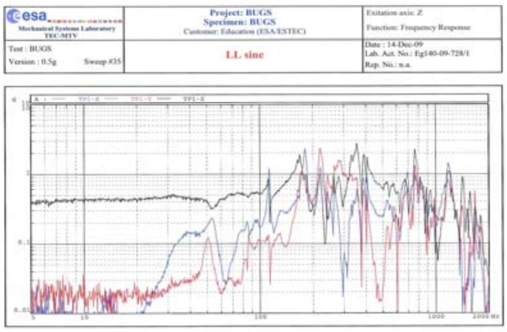

Figure 9 – Test accelerometer, post-random sinusoidal sweep

4. FLIGHT PERFORMANCES

A visual post flight inspection and a preliminary data analysis were performed by the mission team after the recovery of the experiment few hours after the REXUS-7 launch. The mechanical structure of the experiment was recovered in nominal configuration (Fig. 10); it showed the accurate design and sizing of the experiment. A visual inspection of the dynema wires used for thermal cutter and ejection systems demonstrated the right functioning of both these systems for each boom: the wires were cut and not broken (for example due to the vibrations). Fig. 10 shows that both booms were deployed and ejected during the flight. Data recovered from service module housekeeping data confirmed it.

In order to obtain information on the vibration due the boom on the rocket, an analysis using Fourier transformation on the angular velocity data (obtained with gyros onboard Rexus7) has been performed. Fig. 11 shows the frequency spectrum of the angular velocity along the axis of the rocket (blue line) and along a perpendicular axis of the rocket (red line) for the shortest boom. For the shortest boom, achieved data show that the value of first frequency along the rocket axis is about zero, while the frequency value with respect to the perpendicular axis is about 0.12Hz.

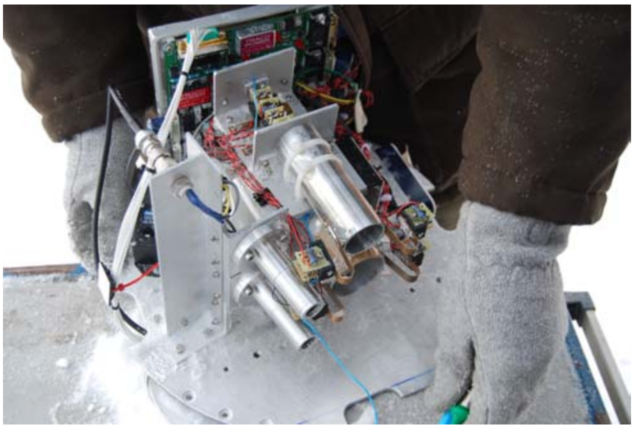

Figure 10 – BUGS experiment after the recovery phase at ESRANGE Space Center.

Fig. 12 shows the frequency spectrum of the angular velocity of the Boom 1 (the longest one). Achieved data show that the vibration frequency along the rocket longitudinal axis is about 0.04Hz (blu line) while the perpendicular frequency is about 0.4Hz (red line). The frequencies that the booms have induced to the rocket are very low; this suggests that both the booms are suitable to be employed in a gravity gradient stabilization system for small satellites, together with a damping system, for example based on magnetic permeable rods [6].

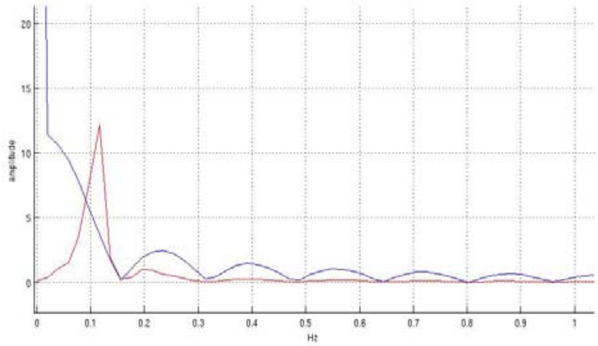

Figure 11 – Boom 2 modal frequency identification

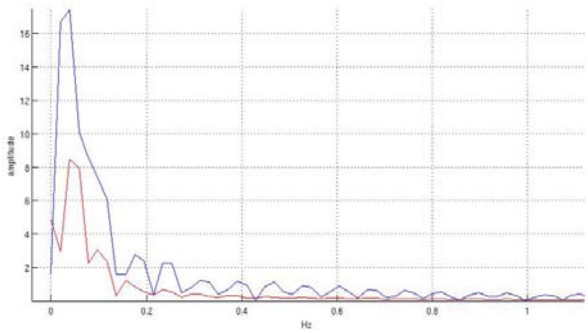

Figure 12 – Boom 1 modal frequency identification

Thanks to the housekeeping data, the profiles of velocities and accelerations of the rocket have been reconstructed. It is clear that the roll velocity decreased when the booms deployments occurred, according to the conservation of angular momentum. Booms performs as yo-yo de-spin system for the rocket. According to the achieved data, it has been evaluated that the part of the rocket in microgravity condition – therefore without motor adapter and nosecone – had a polar moment of inertia of 1.95 kgm^2 and a lateral moment of inertia of 33.19 kgm^2. The distance between the total centre of mass and BUGS centre of mass has been calculated in 84 mm along the X axis. It was not possible with the available data to evaluate the distance between the two centres of mass along the Y and the Z axis, but an estimation was set thanks to the attitude mathematical model described below. The effect of deployment was calculated imposing the conservation of angular momentum before and after the boom deployment; the force resulted about 76 N. A rocket attitude mathematical model was developed with the main purpose of verifying the accuracy of this result. To evaluate the change in the moments of inertia after the boom deployment, a simple CAD model of the rocket in microgravity configuration was drawn, respecting the actual dimensions, moments of inertia and mass. A model of the boom was then added, obtaining new moments of inertia of the whole body. A comparison between the housekeeping data and a simulation obtained with this mathematical model is given in Fig. 13. The simulation was performed for a 76 N force and a distance between the total centre of mass and BUGS centre of mass of 5.7 cm along Y and 0.5 cm along Z (these are the measurements that minimize the error between model and real data). It is possible to notice in Fig. 13 that the model is quite similar to the real behaviour of the boom, confirming that a force of 76 N is possible, and giving a reasonable evaluation of the distance between the centres of mass.

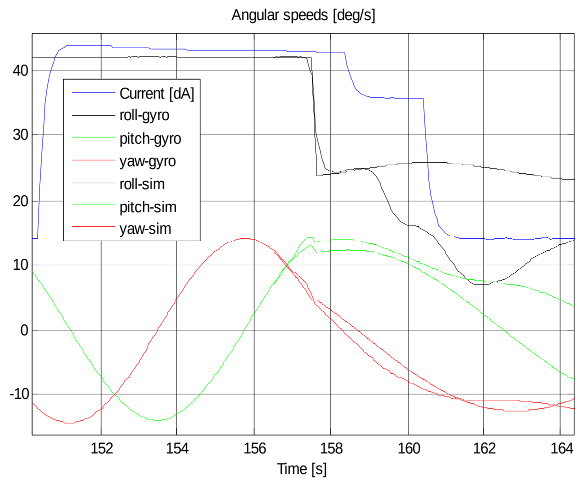

Figure 13 - Comparison between gyroscopes data and model simulation for the boom deployment.

5. CONCLUSIONS

REXUS program provided students with the opportunity to participate in a real space project following all phases, from the concept and design until the launch campaign and data analysis. Both booms of the BUGS experiment were deployed and ejected successfully during the REXUS 7 flight and booms modal frequencies were estimated. The thermal cutter and the ejection systems worked nominally.

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