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Design, AIT, Launch & Early-Operations of Galassia Nano-Satellite

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ABSTRACT

Galassia is the first cubesat built by undergraduate students at the National University of Singapore (NUS) within the education curriculum of the Design Centric Program (DCP). The 2U cubesat carries two primary mission payloads and one secondary mission payload. The primary payloads are the TEC (Total Electron Content) payload and the SPEQS (Small Photon Entangling Quantum System) payload. The secondary payload is an active ADCS (Attitude Determination and Control) module built by students. This cubesat project was developed in an accelerated 2 model philosophy while care has been taken and formulated for its development. In particular, a neat and systematic assembly process was formulated for the CubeSat and this had led to its integration into a Flight Model in July 2015.

This flight model of Galassia was then subject to environment tests at a clean room facilities in Singapore to ensure it has passed the environment test requirements (random vibration, sinusoidal vibration and thermal cycling) prior to its acceptance for flight and launch in with the PSLV (Polar-Satellite Launch Vehicle) C29 from ISRO (Indian Space Research Organization). The launch took place on 16 Dec 2015 (2030 Hours Singapore Time) and Galassia was inserted into a near-equatorial orbit (NeqO) at 550km altitude with 15 degrees inclination angle. The ground communication with Galassia was established in the following orbit (16 Dec 2015, 2218 Hours Singapore Time).

This project has given the students (total about 35) hands-on experience in designing various aspects of the CubeSat and see to it that it got integrated successfully for test, launch and eventual operations. This paper will provide a description of some of the unique experiences the team has made, especially in the systems engineering approach in ensuring a robust design is engineered for the successful launch and operations of Galassia.

1) INTRODUCTION

From 2012 to 2015, a combined team of staff and students from the Faculty of Engineering (FoE) worked together to design, build and test NUS first nano-satellite, Galassia. The educational and technical objectives of this project are:

1. To provide undergraduate students an opportunity to work on satellite systems.
2. To design, build and validate student built payloads.
3. To build up in house satellite system capabilities (eg. payload design, AIT philosophy, ground station, etc.)

Galassia was launched on PSLV C29 as a secondary payload into a near-equatorial orbit, with an altitude of 550 km and inclination of 15 degrees on 16 December 2015.

2) SYSTEM DESIGN OF GALASSIA

Being the first nano-satellite of NUS, a combination of commercial off the shelf (COTS) subsystems with flight heritage together with in house designed payloads were used in the design of Galassia. A total of 2 primary payloads and 1 secondary payload were flown on board the Galassia mission.

2.1) Primary Payload 1

The first primary payload is a Total Electron Content (TEC) Payload. This payload was designed by final year project students. It makes use of a new approach using three equally spaced tones with a known phase relationship to characterize the atmospheric TEC in the ionosphere above Singapore [1]. In this method, three continuous waves (CWs) with center frequencies of (f_0-f_m), f_0, and (f_0+f_m) are sent from the satellite to ground when it is above Singapore where f_0 is the center frequency and f_m is the modulation frequency. The measurement principle is based on the different delays for the signals with three frequencies. At the ground station, the signals with three frequencies need to be separated. The terms with center frequencies of (f_0-f_m), and (f_0+f_m) are mixed with the f_0 signal, respectively.

The resulting two signals after mixing both will have a center frequency of f_m. The phase difference between these two signals, ΔΦ, can be used to calculate the electron density as shown:

$$TEC = 5.97 \times 10^5 \frac{{f_0}^3}{{f_m}^2} \Delta\Phi \qquad (1)$$

where TEC is in the units of TECU (1 TECU = 10^{16} electrons/m^2) ; f_0 is the center frequency; f_m is the modulation frequency; and ΔΦ is the phase difference.

The proposed three tone method in this payload uses the VHF band and gives a high range of TEC measurement of 0 – 1400 TECU and a sufficiently high resolution of around 1 TECU.

This measurement of TEC is important for the correction of propagation effects on applied radio systems such as the Global Positioning System (GPS) [2]. TEC measurements have also been shown to be useful in earthquake monitoring, modelling and prediction in which a significant reduction in TEC is observable at least 3 days before major earthquakes [3].

The TEC payload operates at 5V, 1A nominally and is turned on and off directly from a power switch. All data processing is done on the ground and no data storage is required for this payload.

Figure 1: TEC Payload Engineering Model

2.2) Primary Payload 2

The second primary payload is the Small Photon Entangling Quantum System (SPEQS) payload which is developed by the Centre for Quantum Technologies (CQT) in NUS. This payload makes use of a process called Spontaneous Parametric Down Conversion to generate photon pairs which can be used to establish a quantum communication link between two sites [4].

Both generation and detection of photon pairs are done within the 10 cm × 10 cm payload in a space environment and serves as the first step to verify if quantum communication is feasible in space.

Figure 2: SPEQS Payload Engineering Model

The outcome of this experiment will be the first step to demonstrate a space qualified quantum light source which has the potential to solve the challenges of establishing a global satellite based Quantum Key Distribution network [4].

The SPEQS payload consumes approximately 1.4 W of power during normal operation [4] and communicates with the OBC through the Universal Asynchronous Receiver/Transmitter (UART) interface. The concept of operations of the SPEQS payload is shown in Figure 3.

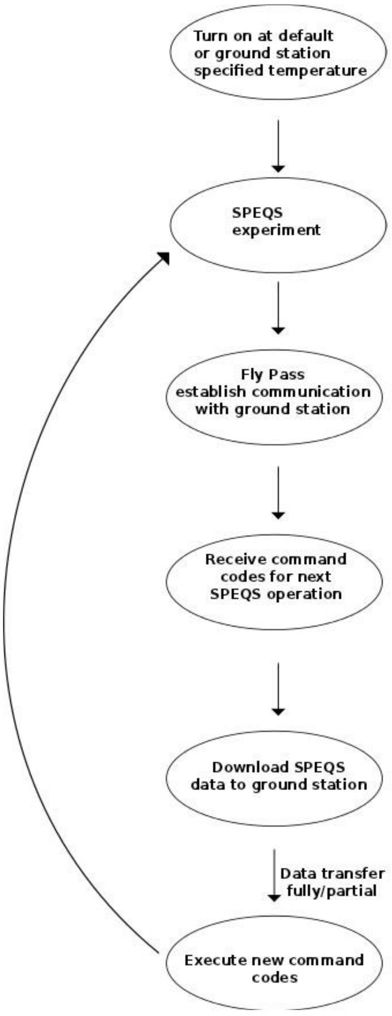

Figure 3: SPEQS Payload Concept of Operations

2.3) Secondary Payload

An experimental active ADCS Payload (ADCS-EP) is flown on Galassia as a secondary payload to be turned on after the two primary missions are completed. This payload is designed by a final year project student and will be used to perform active attitude control experiments such as detumbling, sun pointing and manual pointing which will contribute to a build-up of knowledge for future missions that require active attitude control [5].

The ADCS-EP is essentially a standalone electronics board featuring a 3-axis magnetometer, 3 axis gyros, sun sensor amplifiers, magnetorquer drivers and a microcontroller unit to perform the attitude determination and control experiments. Connected to the board are the sun sensors, magnetorquers and additional gyros which are mounted on the COTS solar panels from GOMSpace

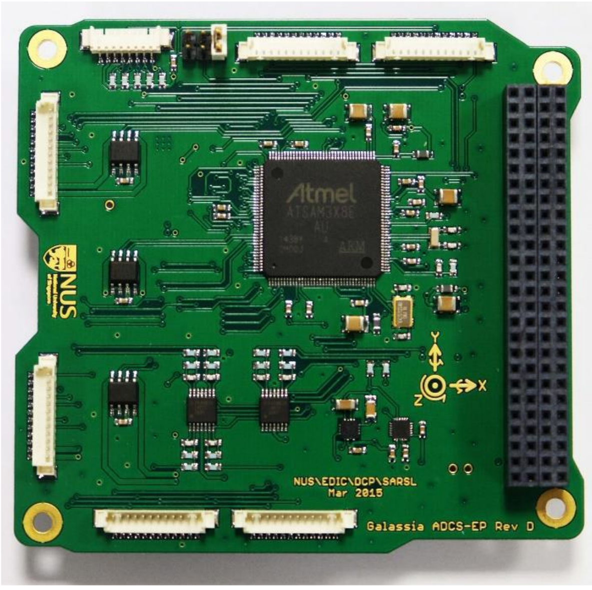

Figure 4: ADCS-EP (Engineering Model)

The ADCS-EP operates at 5V and communicates with the OBC and the rest of the satellite bus over I2C by integrating the Cubesat Space Protocol (CSP). This allows ease of data transactions across all nodes including the ground station without inter-dependency on other subsystems. The power consumption for various modes of operation is shown in the Table 1.

Table 1: Power Consumption of ADCS-EP

Mode	Worst Case (mW)	Average (mW)
Off	0	0
Standby	1200	1050
Detumbling	1450	700
Spin-up	1450	700
Sun Pointing	1450	1250
Manual Pointing	1450	1250

2.4) Passive Magnetic Attitude Control

As there is no mission requirement for pointing accuracy on Galassia, a passive attitude control system is implemented for detumbling the nano-satellite. The concept used is similar to that of the Delfi-C3 [6] in which a magnetic field is created to align the satellite with the earth's magnetic field, slowing down the spin of the satellite after launch.

The passive magnetic attitude control on board Galassia was designed using a permanent magnet controlling one axis and two sets of hysteresis rods controlling the other two axes. The material for magnets chosen was AlNiCo5 and the material chosen for the hysteresis rods was PermeNorm 5000H2. It was also simulated that the hysteresis rods should be kept away from the permanent magnets as the permanent magnets may saturate the hysteresis rods.

The passive attitude control boards that housed the magnets and hysteresis rods were own self designed and tested for flight by NUS undergraduate students [7].

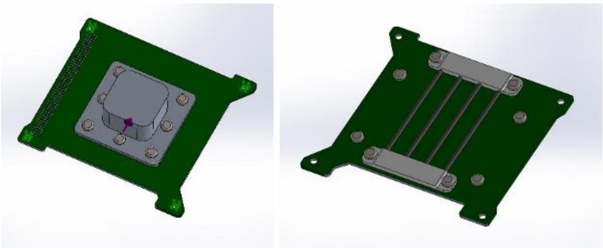

Figure 5: Passive ADCS, Magnets (left), Hysteresis Rods (right)

2.5) Satellite Bus

A COTS satellite bus with subsystems from GOMSpace and Innovative Solutions In Space (ISIS) was used for the Galassia mission. The satellite bus consists of the 2U ISIS Cubesat Structure, the NanoPower P31u (Electrical Power Subsystem), NanoMind A712D (On Board Computer), NanoCom U482C and ANT430 (Telemetry Subsystem), the NanoHub and the ISIS deployable antenna system.

2.6) Satellite System Specifications and Configuration

Careful planning and reviews were conducted to determine the satellite configuration and the order in which the subsystems were to be stacked. Table 2 shows Galassia's system specifications.

Table 2: Galassia System Specifications

System Specifications	
Bus	2U Cubesat
Dimension	100 mm × 100 mm × 200 mm
Mass	1.640 kg (measured)
Communication	UHF
Power	2 W
Battery	20 Whr Li-Ion
Solar Panels	GaAs Cells
Flight Computer	ARM 7
Attitude Control	Permanent Magnets and Hysteresis Rods

The final configuration chosen is illustrated in Figure 6 and Table 3 shows the stacking order.

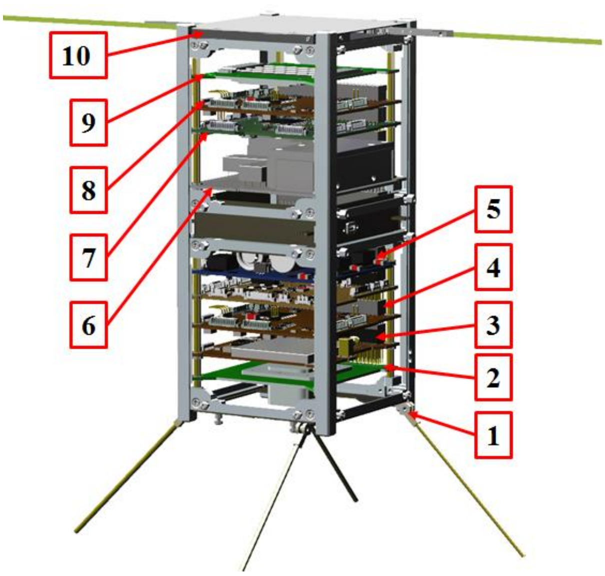

Figure 6: Galassia System Configuration

Table 3: Galassia Stacking Order

Stacking Order (Bottom to Top)	
1	GOMSpace Deployable Antenna (UHF)
2	Passive Magnetic Attitude Control (Magnets)
3	NanoCom (TT&C)
4	NanoMind A712D (OBC)
5	NanoPower P31u (EPS)
6	Primary Payload 2 (SPEQS)
7	Secondary Payload (ADCS-EP)
8	Primary Payload 1 (TEC)
9	Passive Magnetic Attitude Control (Hysteresis Rods)
10	ISIS Deployable Antenna (VHF)

2.7) Galassia Modes of Operation

Galassia is designed to have 4 modes of operation, namely:

1. Initialization Mode, in which the system turns on all the subsystems and deploys the antennas if it was not previously done. The satellite will also enter this mode if it has undergone a hard reset which will be called the recovery mode.

2. Contact Mode is entered when ground communication is established with the satellite. In this mode, the satellite stops beaconing and prepares to perform commands sent via the ground station.

3. Autonomous Mode is entered either by a ground command or when there are no ground commands for a period of time that leads to a timeout. In this mode, the satellite starts beaconing and performs typical housekeeping functions.

4. Power Saving Mode is triggered when the battery voltage falls below a set threshold. In this mode, experiments are not allowed and only the critical subsystems such as power, communications and computer are turned on.

Figure 7 shows a state diagram of the 4 modes of operation.

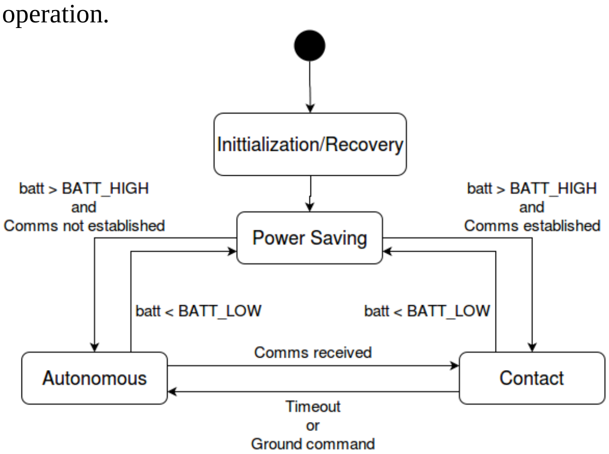

Figure 7: Galassia Modes of Operation

3) ASSEMBLY INTEGRATION AND TESTING

A two model philosophy is used in the development of Galassia. This assembly, integration and testing (AIT) philosophy consists of two models as follows:

1. Engineering Model (EM), in which a flatsat was set up to perform hardware and software testing with easy access to all subsystems and payloads.

2. Flight Model (FM), which was tested at a system level to verify that the satellite will be able to withstand the harsh space environment.

3.1) Engineering Model Development

A flatsat concept is used for the EM development. This concept allows ease of access to the various subsystems for testing and also allows various revisions of the payloads to be easily integrated with the bus without disassembling the entire satellite.

Figure 8: Galassia Engineering Model (Flatsat)

During this phase of development, various revisions of the payloads are integrated and tested with the COTS satellite bus. The EM development lasted from August 2013 to December 2014.

In parallel to the development of the flatsat, an assembly dry run was also conducted by the team of research staff and undergraduate students [8]. In this phase, printed circuit boards with the same dimensions as the actual flight models were stacked up in the configuration that resembles the flight model. This was done to prepare the team as well as give the team confidence before the actual assembly. The wire harness models are also developed during this dry run to optimize the length of the wires that will be used in the flight model.

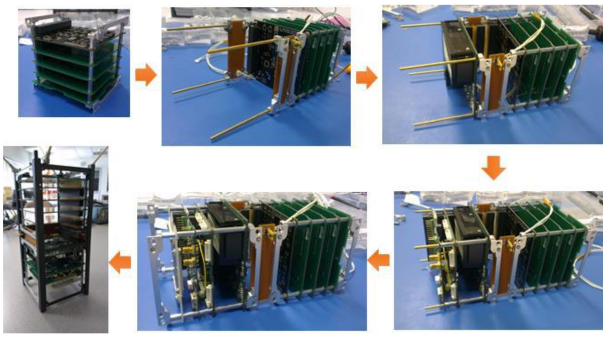

Figure 9: Galassia Assembly Dry Run

Towards the end of the EM development phase, a full orbit simulation was conducted on the flatsat. This simulation is done to test that both the hardware and software are operational for all modes of operation (initialization and deployment of antennas, autonomous mode for in-orbit operation, contact mode for primary payload experiments and power saving mode).

3.2) Flight Model Development

The Galassia FM was assembled by a team of undergraduate students and research staff in a class 10,000 cleanroom within the NUS Satellite and Airborne Radar Systems Laboratory.

Figure 10: Undergraduate Students Assembling FM

Figure 11 shows the FM assembly process that was tested and rehearsed during the assembly dry run in the EM phase. This phase lasted between the periods of December 2014 to July 2015.

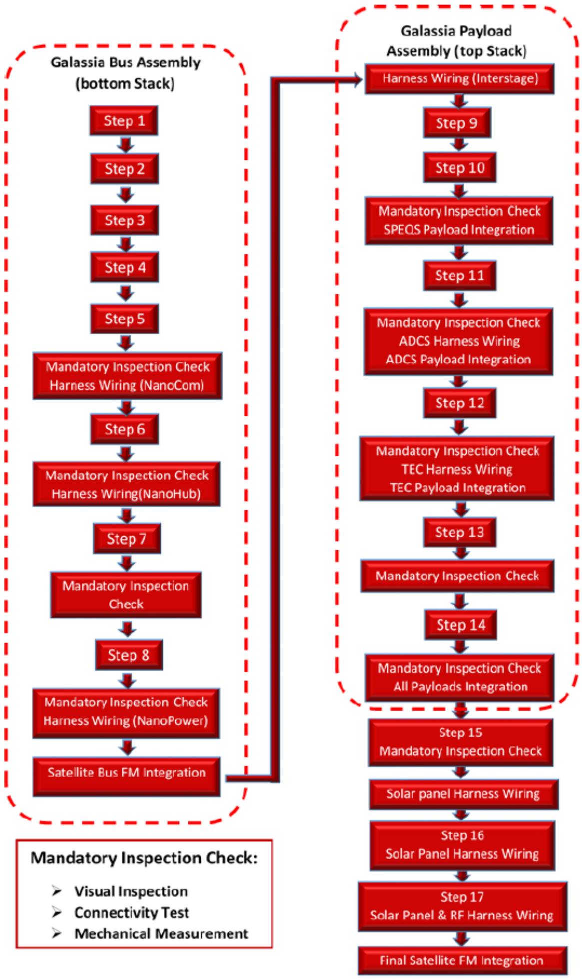

Figure 11: Galassia Assembly Sequence

A series of mandatory inspection and checks were done at key points by a research staff assigned to be the designated quality inspector during the assembly. The points are shown in Figure 11. These checks include a visual inspection to ensure no mechanical damage caused during assembly and a connectivity test to ensure that all electrical connections are routed correctly. Mechanical measurements of mass and dimensions were also taken to ensure that all parts fit before assembly.

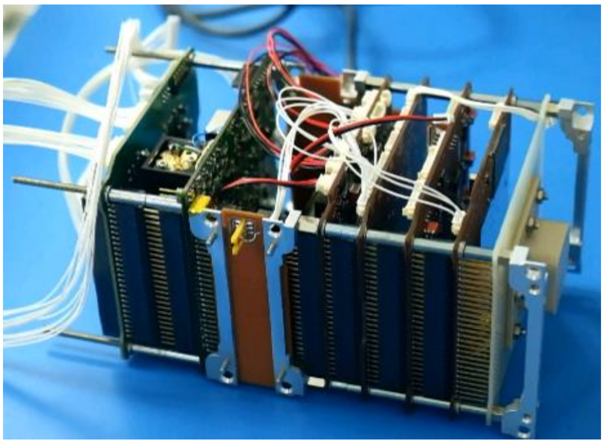

Figure 12: Galassia FM During Mandatory Check

In addition to the checks, an assembly activity log was kept to track the work done, to note down any significant issues and the personnel working on the FM. This log was updated daily during the FM development period.

3.3) Environmental Testing

Environmental testing of Galassia was conducted at ST Electronics (Satellite Systems), a local company in Singapore. ST Electronics (Satellite Systems) was chosen as the facility is able to conduct both the vibration and thermal tests in a class 100,000 clean room environment for satellite development. These tests were initially planned to be a week long but due to unforeseen circumstances such as the breakdown of the shaker table, the tests were done from August to September 2015.

As there was no prior qualification test done on the Galassia EM, testing at Proto Flight Model level was required by the launch service provider (ANTRIX/ISRO) for vibrational tests. Table 4 and 5 shows these test levels that were required by ISRO given in the interface control document. The thermal vacuum test was done to give the team a higher level of confidence that the in house subsystems will survive the space environment.

The axis definitions for the vibrational tests are shown in Figure 13 where the term "longitudinal" is in the reference frame of the rocket, corresponding to the X- and Y- axis of the satellite and the term "lateral" corresponds to the Z- axis of the satellite [9].

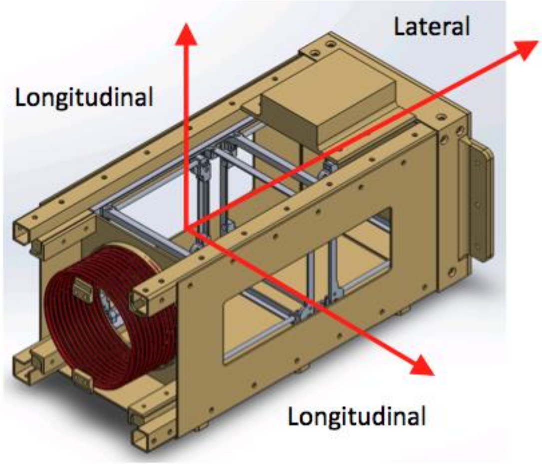

Figure 13: Axis Definition for Vibrational Tests

The vibrational test profiles are as shown in Table 4 and 5.

Table 4: Sinusoidal Vibration Test Levels

	Frequency Range (Hz)	Proto Flight Model Test Level
Longitudinal Axis	5.0 – 10.0 10.0 – 100.0	10 mm (0 – peak) 4.5 g
Lateral Axis	5.0 – 8.0 8.0 – 100.0	10 mm (0 – peak) 4.5 g
Sweep Rate		One Upsweep 4 Oct/min

Table 5: Random Vibration Test Levels

Frequency (Hz)	PSD (g^2/Hz)
20	0.002
110	0.002
250	0.034
1,000	0.034
2,000	0.009
g RMS	6.7
Duration	1 min/axis

The test philosophy was such that either a full functional or reduced functional test was carried out before and after a "damaging" environment test. In addition, at least one pre and post low amplitude sine sweep was carried out in between the environment tests and the graphs were compared. Figure 14 shows the test sequence for a sinusoidal vibration test in the lateral axis. A similar approach is used for all 3 axis for both the sinusoidal vibration and random vibration tests.

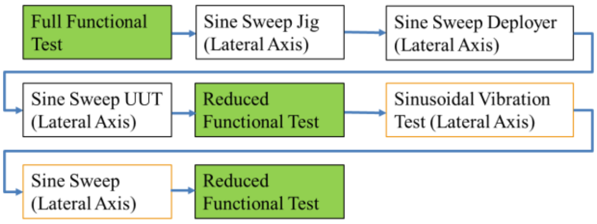

Figure 14: Test Sequence

In the full functional test, all the functions of the satellite are tested while in a reduced functional test, only the essential functions such as I2C communication between the subsystems, retrieving data and the sending of commands are tested.

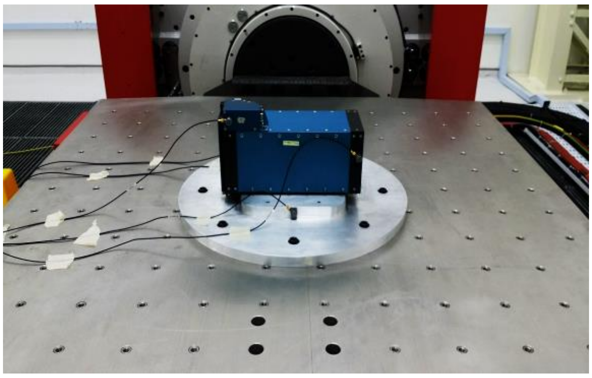

Figure 15: Galassia in Deployer on Vibration Table

During the vibration tests, tri-axial and uni-axial accelerometers are placed on various locations on the deployer. These locations were identified based on FEA Natural Frequency Vibration Simulations. Figure 16 shows the location of the accelerometers for the sinusoidal vibration test in the lateral axis.

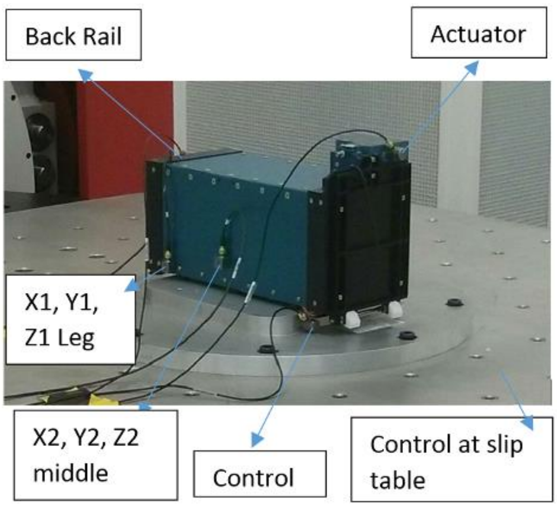

Figure 16: Accelerometer Placement for Sinusoidal Vibration Test

The outcome of the sinusoidal vibration test done in the lateral axis is shown in Figure 17. It is observed that there is no visible damage done to the satellite. The satellite also met all functional requirements after being tested at levels that were within the PSLV launch vehicle requirements.

The sinusoidal vibration test in the lateral axis suggest the following:

- The first natural frequency of the FM Assembly occurs on the Back Rail of the deployer at around 275 Hz.

- The center frequency for the first peak is at 345 Hz, and the frequency increment Δw at the half power point is:

  $$285 \text{ Hz} - 215 \text{ Hz} = 70 \text{ Hz} \qquad (2)$$

  This gives us a Q factor of 3.9.

- Below 70Hz there is no observable peak and hence no natural frequencies at any of the locations measured.

A total of 5 other vibration test (both sinusoidal and random) were done for all 3 axis. These observations were consistent throughout the rest of the tests and complies with the launch requirements provided by ISRO.

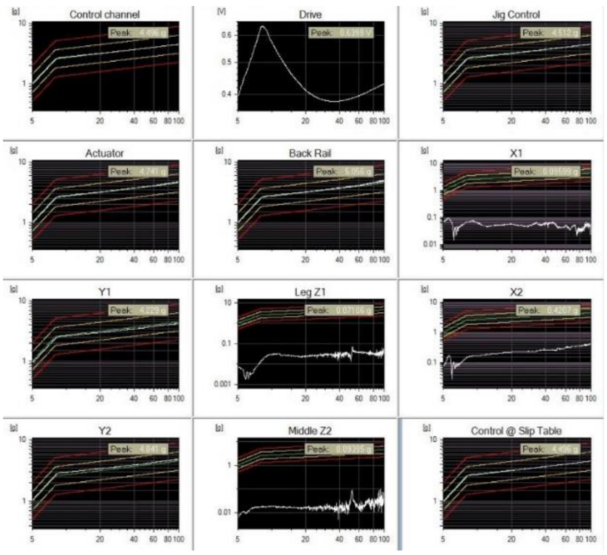

Figure 17: Sinusoidal Vibration Test Profiles

Following the vibrational tests, a thermal vacuum test was conducted on Galassia. Even though this is not a launch requirement, the purpose of conducting a thermal vacuum test is to verify the performance of

Galassia through functional tests in a realistic simulation of the space environment on ground.

A profile as shown in Figure 18 and Table 6 was generated through a study of successful satellite missions [10]-[14] as well as the military standard test requirements for space vehicles [15]. The key test points such as payload operation and antenna deployment in a vacuum environment are also included in the profile.

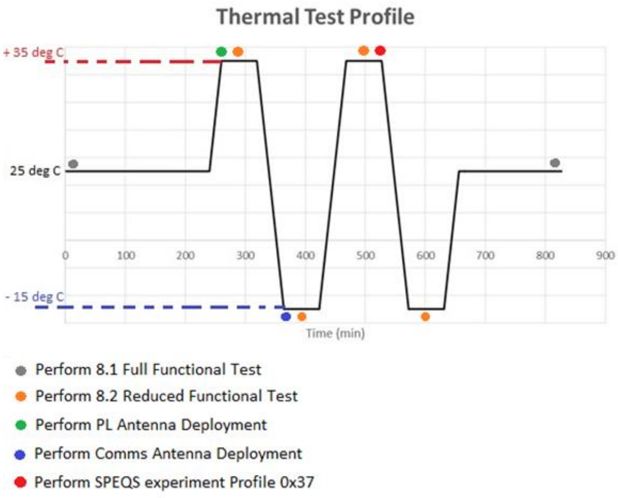

Figure 18: Galassia Thermal Vacuum Test Profile

Table 6: Summary Thermal Vacuum Test Profile

Parameters	Condition
Start Cycle	Hot
Ambient Temperature	25°C
Vacuum Pressure	10^{-5} Torr
No. of Cycles	2
Dwell Time	1 Hour Cold Soak 1 Hour Hot Soak
Temperature Ramp	2°C/min
Range	- 15°C to + 35°C

A visual inspection and functional test is performed on Galassia prior to the start of the tests. 2 temperature sensors provided by the test facility were mounted on the satellite top cover and a side panel to measure the satellite surface temperature. Another sensor was mounted on the base of the test jig which acted as a control point. Figure 19 shows the thermal profile of the satellite with respect to the external temperature in a vacuum environment.

A total of 4 functional checks were performed during the hot/cold soak phases. Both the full and reduced functional checks performed during these phases are similar to those used during the vibration tests.

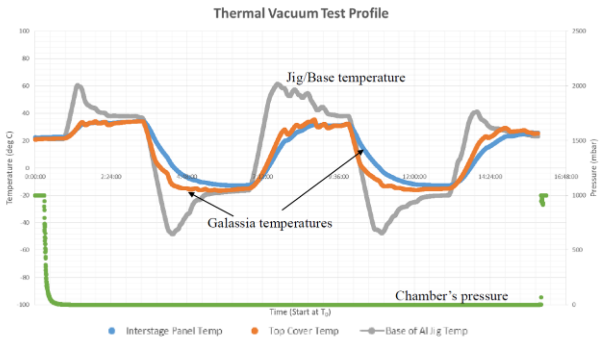

Figure 19: Galassia Temperature During Thermal Vacuum Test

Having passed both the vibration tests and thermal vacuum tests, Galassia was stored in the cleanroom within the NUS Satellite and Airborne Radar Systems Laboratory waiting to be shipped nearer the launch date. The satellite was tested at regular intervals during the storage period to ensure that all systems are operating nominally before shipment.

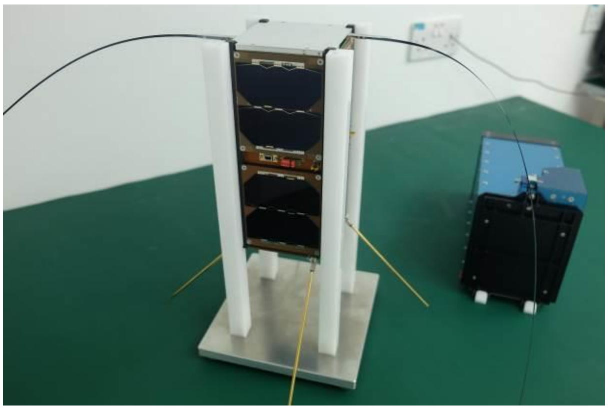

Figure 20: Galassia & Deployer Awaiting Shipment

4) LAUNCH CAMPAIGN

The nano-satellite launch campaign lasted from 14th November 2015 to 8th December 2015 and involved 2 of the research staff. Careful scheduling was considered to ensure enough buffer time should unforeseen circumstances occur during the launch campaign. Within this period, Galassia was carefully shipped via air freight from NUS to the ISRO launch site in the Sriharikota, Andhra Pradesh, India. A data logger, Shocklog 298, was placed inside the pelican case containing the satellite to monitor any form of impact during transportation.

Upon arrival at the launch site, Galassia was kept in a class 100,000 material air-lock cleanroom. As cleanroom conditions needed to be established, the nano-satellite was only unloaded and inspected after 24 hours upon arrival.

Figure 21: Unloading Galassia at Launch Site

After unloading the nano-satellite, information from the data logger was first obtained to ensure that there was no major impact on the satellite during the transportation.

Next, functional checks similar to the ones done previously were carried out to check that the transportation did not cause any internal damage to the nano-satellite. The satellite was then stored again as functional checks were still ongoing for the larger satellites.

Before handing over the satellite to the ISRO team for integration to the launch vehicle, a final functional check was done through the open face of the deployer. This was done to ensure that the battery is sufficiently charged till the day of launch, the satellite is operating nominally and that all deployable antennas are properly stowed.

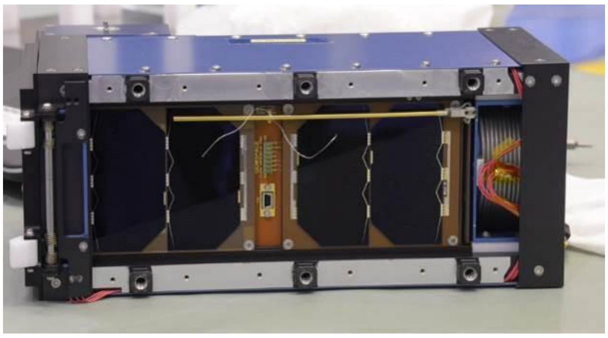

Figure 22: Final Functional Check

After the final functional check, both the NUS team and ISRO team worked together to integrate the nano-satellite deployer to the 4th stage of the launch vehicle. Both teams were involved in checking that the wire harnesses for the power and signal harnesses from the launch vehicle to the satellite deployer were done correctly.

Figure 23: NUS Team (left) and ISRO Team (right) Integrating Galassia to the Launch Vehicle 4th Stage

After successful integration of all the satellites, the launch vehicle 4th stage was containerized, transported and integrated to the rocket. Here, a final visual inspection was done and the remove before flight connectors were removed.

On 16 December 2015 at 2030 Hrs (SGT), Galassia was successfully launched as a piggyback payload on board the PSLV C29 into a 550 km orbit with 15 degrees inclination together with 5 other Singapore built satellites [16].

Figure 24: PSLV C29 Launch [16]

Figure 25: Successful Launch of 6 Singapore Built Satellites

5) EARLY OPERATIONS AND PRELIMINARY RESULTS

Early Operations

Back in the NUS ground station, research staff and students prepared to make contact with Galassia. The first contact was established on the first pass on 16 December 2015, 2218 Hrs (SGT).

Following the successful contact of Galassia, more in orbit data was collected during the early operations phase before conducting payload experiments. This was done to check and confirm that all antennas had been deployed, the batteries were charging properly and the satellite has detumbled.

During the early operations phase of the Galassia mission, key parameters such as battery voltage, internal temperatures and external temperatures were taken for a full orbit. This was done to characterize the space environment before attempting to perform the payload experiments. Figure 26 shows a set of data for Galassia's internal and external temperatures for a full orbit.

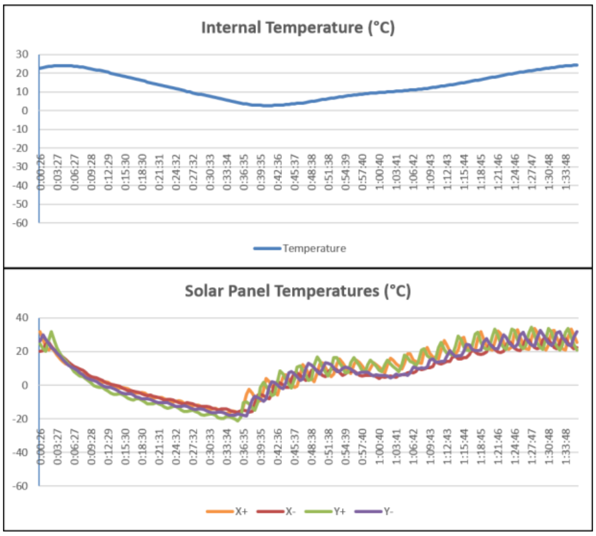

Figure 26: Temperature of One Full Orbit

A near equatorial orbit with 550 km altitude, 15 degrees inclination gives Galassia approximately 15 passes above the ground station in Singapore daily with each pass being about 10 – 12 minutes long. It was also observed during early operations that not all passes were suitable for contact with the satellite. This was attributed to factors such as noise and congestion in the UHF amateur radio band that was used for communication. To optimize contact with the satellite, the sources of noise were identified and good passes were chosen for passes that did not coincide with the direction of the noise. It was further established that a good pass can be further optimized when it is above 20 degrees elevation as there will be a longer contact time. With these factors in place, a good pass was chosen to conduct payload experiments and downloading of experiment data.

Preliminary Results

At the time of this writing, Galassia has completed the set of in orbit tests and is beginning to conduct payload experiments.

The payload experiments (TEC, SPEQS and ADCS-EP) are always run individually. This approach is adopted to ensure that the power consumption is always within the budget and that unforeseen errors can be mitigated easily.

Figure 27 shows the preliminary results of the TEC experiment in which the 3 continuous waves (f_0-f_m, f_0, and f_0+f_m) from Galassia are captured in the ground station. The peaks in Figure 27 have been verified to be coming from the Galassia which also confirms that the TEC payload is functional in space. Currently, the peaks were detected at up to -85 dBm with a sampling noise floor from -105 to -90 dBm. Further optimization is currently being done to get a better signal to noise ratio (SNR) to precisely extract the phase information for calculation of the TEC value.

During the course of operations, in-orbit experiments onboard the SPEQS payload have also been successfully downloaded and sent to the Centre for Quantum Technologies (CQT) for analysis. Colleagues at CQT have confirmed that the photon correlations onboard the SPEQS exhibit a contrast of 97% ± 2%, matching ground-based tests [17]. The results have validated the design of both the photon-pair generation and the polarization-measurement system.

Additionally, noise events (dark counts) throughout the SPEQS experiments have been monitored to see the effect from radiation towards the components used in the payload. The compatibility of the in-orbit polarization correlations with baseline measurements proves that the components have not been influenced so far by in-orbit radiation. Further operation will study the long-term performance of the payload, and the results will be used to inform the design of the next iteration of the SPEQS payloads.

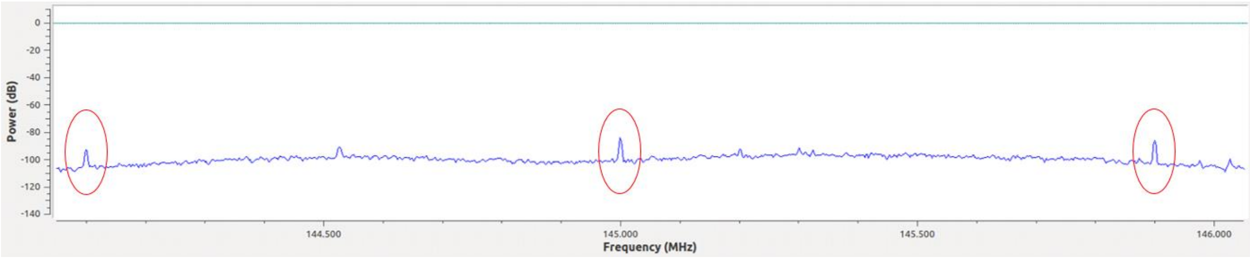

Figure 27: Three Tones from the TEC Payload as Captured at the Ground Station

6) CONCLUSION

In conclusion, Galassia has met both its technical as well as educational objectives and is currently in orbit with good health status at the time of this writing. The project has also brought NUS a step forward in designing and building space systems together with the accompanying ground telemetry systems. The next phase of development will be to attain as much in orbit data as possible as well as planning for future missions.

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