Sanket - Technology Demonstrations of Antenna Deployment System on PSLV Stage 4 Orbital Platform

Karan Jagdale, Mrigi Munjal, Prashant Kurrey, Ashay Wakode, Pushkar Lohiya, Puneet Shrivas, Anmol Sikka, Aniruddha Ravindra Ranade, Sanskriti Bhansali, Abhishek Kejriwal, Amrutha Lakshmi Vadladi, Ankit Kumar, Atharv Savarkar, Hemant Dilip Gidewar, Hrithik Agrawal, Mohit Dhaka, Pranav G Kasat, Ritul Shinde, Shreya Laddha, Adesh Yadav, Akshat Mehta, Dhanush S, Ishan Phansalkar, Jayant Saboo, Kriti Verma, Leena Chaudhari, Navjit Debnath, Shreeya Shrikant Athaley, Shreyas Sabnis, Vidushi Verma, Vineet Gala, Yatin Jindal
Student Satellite Lab, Aerospace Department, IIT Bombay, Mumbai, Maharashtra 400076, India*

An Antenna Deployment System has become an essential component of any pico- or nano-satellite design due to space constraints during launch. The Sanket mission is a technology demonstration that is designed to be flown on the Indian Space Research Organization's PSLV Stage-4 Orbital Platform (PS4-OP) [2] and aims to qualify the team's Antenna Deployment System in Ultra High Frequency (UHF) band (ADS) to a TRL 7 in Low Earth Orbit (LEO). Sanket, i.e. the complete system, comprises an ADS and an auxiliary system. The purpose of the auxiliary system is to test the ADS on PS4-OP simulating a 1U CubeSat mission life cycle and conditions. Sanket will be mounted on PS4-OP which remains in LEO for around 6 months. Our Antenna Deployment System is developed as an independent module that is compatible with typical CubeSat sizes 1U, 2U, and 3U.

I. Nomenclature and acronyms

ADS	=	Antenna Deployment System
CW	=	Continuous Wave modulation
Downlink	=	Signal transmitted from deployed antenna to Ground station
FOS	=	Factor Of Safety
GFSK	=	Gaussian Frequency Shift Keying modulation
HM	=	Health Monitoring
ISRO	=	Indian Space Research Organization
LEO	=	Low Earth Orbit
OOK	=	On-Off Keying
PCB	=	Printed Circuit Board
PSLV	=	Polar Satellite Launch Vehicle
PS4-OP	=	PSLV Stage 4-Orbital Platform
SPDT	=	Single Pole Double Throw
Telemetry	=	Signal transmitted from antenna on PS4-OP
Telecommand	=	Signal transmitted to the antenna of PS4-OP
TRL	=	Technology Readiness Level
UHF	=	Ultra High Frequency
Uplink	=	Signal transmitted to the deployed antenna

II. Introduction

As of 31st May 2018, 855 CubeSats have been launched. By using a logistic model and considering that the launches keep following the current tendency, one can expect that one thousand CubeSats will be launched by 2021 [3].

*Student Satellite Program, IIT Bombay is an initiative taken up by the students to build a centre of excellence in space science and technology at IIT Bombay. The first satellite, Pratham [1], under this program, was launched on board the PSLV-C35 on 26th September 2016. The satellite's payload was to generate data on the total electron count (TEC) in the atmosphere. After launching Pratham, the team now works on designing space systems for CubeSats. With this objective, Antenna Deployment System and Star Tracker based Attitude Determination System are being developed. They are aimed to be tested on PSLV's Orbital Platform. URL: `https://www.aero.iitb.ac.in/satlab/`

India is also seen to be following the same suit. As the number of CubeSat missions in India continues to grow, the need for indigenously developed, reliable communication systems becomes more pressing. Various international firms manufacture and sell Antenna Deployment Systems for CubeSat applications. However, these are associated with steep costs and accessibility issues.

Antenna deployment systems are a critical single point of failure of CubeSats. Making reliable ADS consumes plenty of time for student teams working on CubeSat missions. A low-cost ADS compatible with the standard 1U/2U/3U sizes will be developed and demonstrated by this mission which will benefit future CubeSat missions by reducing costs and facilitating the teams in better payload exploration.

The mechanism used for deployment of the antenna is a burn-wire mechanism, wherein the trigger is caused by thermally cutting the nylon thread that holds the antenna in the undeployed state. A nichrome resistor based circuit is used to cut the nylon thread. After deployment, periodic uplink and downlink will be established with the antenna to establish the working of the ADS for a prolonged period. The PS4-OP provides a telemetry and telecommand interface. Telemetry will be used to obtain the critical data of the system which helps to monitor the system status and health popularly known as Health Monitoring (HM) data. Telecommand will be used for configuring the system in orbit as well as to Kill or Reset the system.

This extended abstract presents the design of the mission, results of the antenna and structural simulations, and electrical and mechanical testing of the ADS. Conclusions on the design decisions made on the basis of the mission requirements are presented in the final section.

The design approach followed is based on the V-model concept of Systems Engineering. The team has already launched its first satellite Pratham in the year 2016. The experience has established rigorous Quality Assurance practices in the team [4]. Maintaining Requirement Document, Interface Control Document, and performing Failure Mode and Effect Analysis are standard Systems Engineering practices followed in the team.

The team has been perfecting the design of the Antenna Development System for two years. The previous design was presented at the International Conference on Small Satellites held in Hyderabad, India in Feb 2019. The paper titled "Design Approach to Antenna Deployment System for Nano-Satellite Applications" co-authored by team members was selected for publication as a chapter in the book titled "Advances in Small Satellites" published by Springer Singapore [5].

Table 1 Sanket System Specifications

Mass of Sanket	482 grams
Mass of ADS	100 grams
Size of Sanket	Standard 1U
Dimensions of ADS	9.8 cm x 9.8 cm x 0.86 cm
Frequency band	Amateur UHF
Deployment mechanism	Nichrome burn wire
Antenna	Half wave Dipole
Antenna gain	>0dB
Power consumption during deployment	<2 Watt
Downlink	OOK, CW, Beacon
Uplink	GFSK modulation

III. Concept of Operation

After deploying all the satellites, the PS4-OP will power up the system. After powering up, Sanket will check crucial Health Monitoring parameters and enter in the system check mode. If the parameters are found to be in the normal range, Sanket will enter standby for deployment mode. The Health Monitoring data is obtained on the ground using the PS4-OP telemetry. If the data obtained by the telemetry indicates normal operation of Sanket, then a telecommand will be sent to initiate antenna deployment and Sanket will execute pre-deployment mode. In this mode, Health Monitoring data will be generated more frequently to closely monitor the deployment event. After antenna deployment, Sanket will enter in post-deployment mode and the rate of Health Monitoring data generation is lowered. If the Health Monitoring data shows the system is operating without any defects, the uplink and downlink channels will be turned on and Sanket will enter in nominal mode. And then, it is expected that Sanket will be operational for 4 to 6 months.

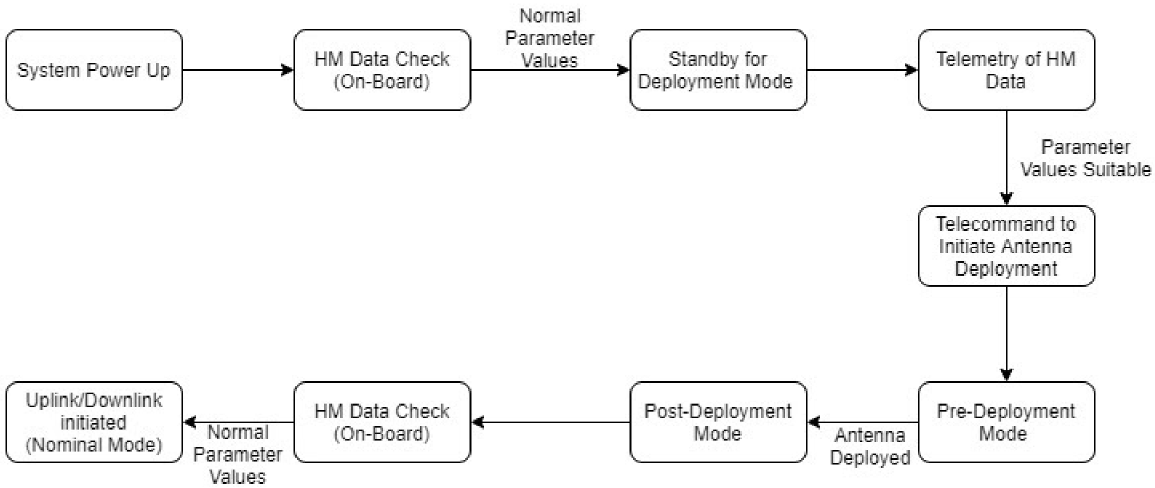


Fig. 1 Flowchart for concept of operation

IV. System Design and specifications

A. Mechanical structure of ADS

The ADS consists of a PCB, stubs, sub-chassis, antennas, interface blocks, deployment detection switch, nylon and nichrome wire. The base seen in Fig 2 is made of acrylic as it was the first ADS prototype manufactured by the team. However a PCB will act as the base for the Antenna Deployment System. The sub-chassis used to stow the undeployed antenna in the coiled state is made of POM (Polyoxymethylene). The stubs and the interface blocks are made of Aluminum alloy (Al6061-T6). A nylon thread holds the PVC sheet (ref Fig 2), used to retain the antenna in an undeployed state and passes through nichrome wire. The nylon thread is cut thermally when current is passed through the nichrome wire on command to deploy the antenna. A Single Pole Double Throw (SPDT) switch is used for deployment detection (ref Fig 4). Mass of the ADS sums up approximately to 100 grams.

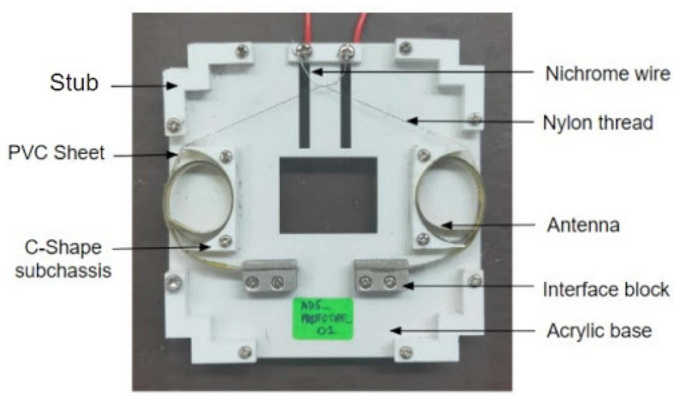


Fig. 2 ADS_prototype_01

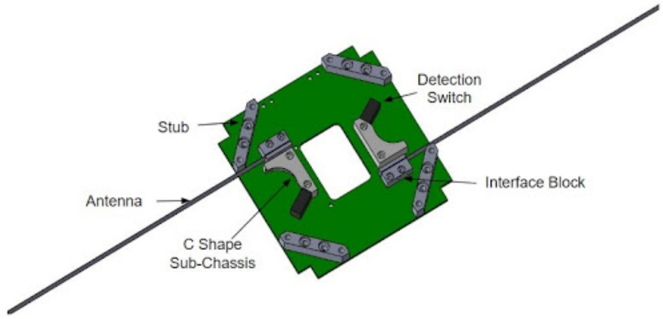


Fig. 3 ADS_001_0007 (CAD model of ADS)

Fig. 4 Deployment Detection Switch

B. Antenna

Dipole antenna used in the ADS is made up of tape spring (Stainless Steel) due to its tendency to regain its shape. The antenna is designed to work in the Amateur UHF band (435 - 438 Hz) and thus has a length of 180 mm approximately making it half-wave dipole. The antenna is modeled in HFSS software for minimum S11 (input port voltage reflection coefficient) in the required frequency band. This design is taken as a starting point to carry out the RF tests on the antenna to measure return loss and Gain.

C. Printed Circuit Board of ADS

The base of the antenna deployment system is made up of a PCB. This PCB houses a burner circuit and an impedance matching circuit. Burner circuit comprises a voltage regulator (TPS50601A-SP) to limit the voltage at the two terminals of Nichrome wire (32 gauge) and deployment detection switches. Tapered traces are used to match the impedance of the antenna to a 50 Ohm SMA Connector. An Interface block is used to interface the antenna to the tapered traces on the ADS PCB (ref Fig 2 and 3).

D. Power regulation and scheduling PCB

This PCB is responsible for power regulation, onboard storage, and scheduling of tasks for the entire system. An EMI filter (SVRMC28) is used to minimize the fluctuations in 28V-10W unregulated power supplied by PS4-OP. A DC-DC converter (SVRHF283R3S) is used to regulate the supply to the operating voltage of the microcontroller. Current limiters (TPS7H2201-SP) are used to avoid overcurrent damage. The microcontroller ATmegaS128 is responsible for the scheduling of tasks, communicating with the PS4-OP for telemetry and telecommand, and collecting Health Monitoring Data (HM Data). The collected HM Data is stored on an EEPROM (AT69170F). Power consumption of the entire system calculated for the different operational modes is as mentioned below-

Table 2 Power Consumption for different Operational Modes

Nominal Downlink Mode	7.84 W
Nominal Uplink Mode	5.89 W
Pre-Deployment Mode	7.92 W

E. RF-communication PCB

This PCB is used for RF communication through the deployed antenna. It incorporates a single transceiver (CC1125) that handles both the uplink and downlink channels which are switched using a circulator. The power amplifier (CMX901) is used to amplify the signal before downlink and LNA (MAAM011229) is used to amplify uplink signals on Sanket. There is one microcontroller (ATmegaS128) on this PCB which is used to program the transceiver and collect the Health Monitoring data from the microcontroller on power regulation and scheduling PCB. On-Off Keying (OOK) modulation is used for downlink whereas GFSK modulation is chosen for uplink. Downlink signal consists of an identity (Name + CallSign) and the Health Monitoring data. Acknowledgment of the instructions uplinked will be taken in telemetry to test uplink.

F. Supporting mechanical structure

The structure is inspired by a standard 1U CubeSat and occupies an area of 126mm x 126mm on the PS-4 platform and 126mm x 433mm x 100mm space after the deployment of the antenna. The total mass of the Sanket system is 480g. The Auxiliary structure (Supporting system for ADS module) is covered with Anodized Aluminium 6061-T6 alloy panels from all sides which serves the purpose of the radiation shielding of the components inside. The Power regulation and scheduling PCB along with RF Communication PCB are stacked horizontally with the help of stubs and the ADS PCB on the top of the 1U structure.The structure was designed in SolidWorks.

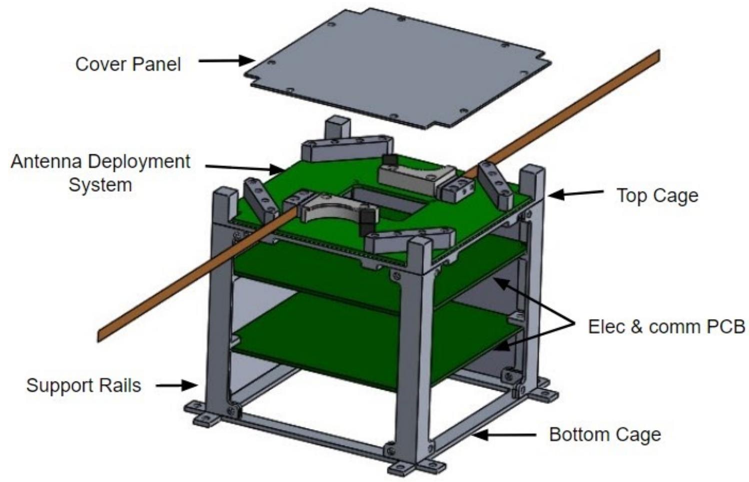


Fig. 5 Exploded view of Sanket

V. Simulation

A. Antenna simulation

Electromagnetic simulations are performed to get an estimate of S11, gain, and radiation pattern of the modeled antenna. Software used for simulation is Ansys HFSS 15.0 CubeSat is modeled as 1U aluminum box and PS4-OP as a cylinder of diameter 2m and length 2m. Simulations are performed on the UHF range. Pole length of a dipole antenna and placement of poles of CubeSat is modified to get optimum results.

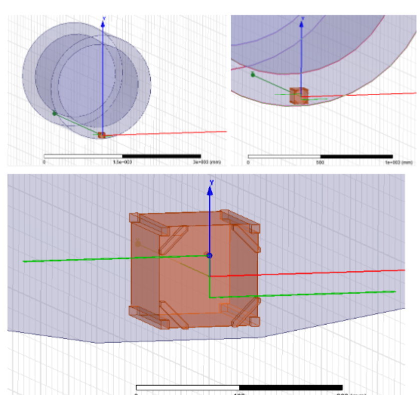


Fig. 6 Antenna Simulation Model

B. Structural simulations

Structural simulations such as Static, Harmonic, Modal, and Random vibrations for PSLV launch loads are performed on the structure in ANSYS. Stress analysis is carried out on the simulated structure, the design failures found are rectified in the next design of the structure. This iterative process is followed for designing the structure for the system which ensures that the system is safe to fly on the PSLV and no part of it is damaged during the flight.

Joints and Contacts Modelling:

- **Screws/Nut-bolt**: Concentric surfaces are interfaced using Fixed joint.
- **Adhesives**: Bonded contact is used to simulate bodies joined by adhesives.

The Modelling of joints and contacts is performed in similar ways as done in [6].

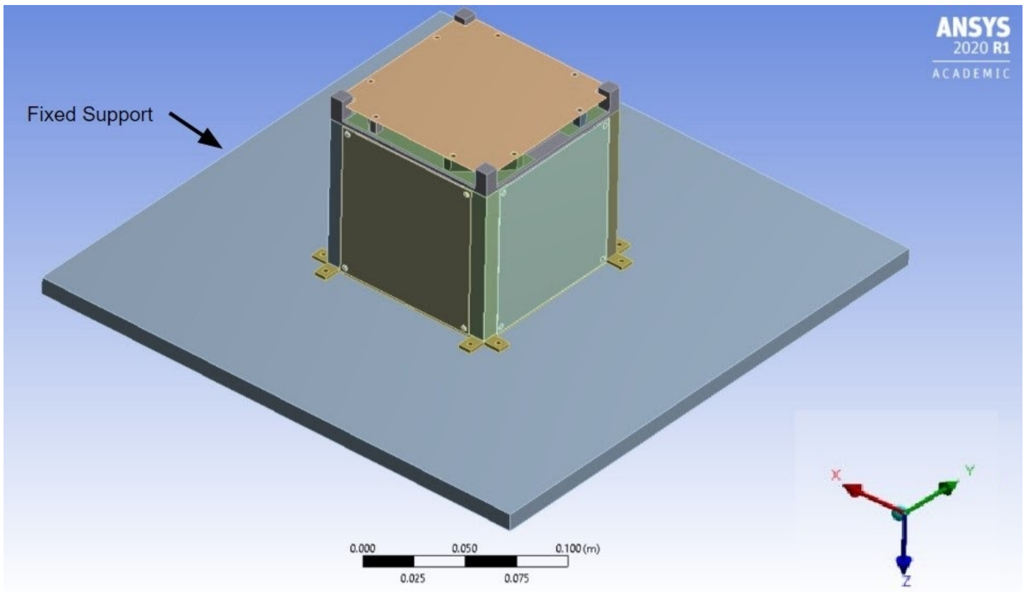


Fig. 7 Boundary condition for simulation

Launch loads:

- **Static Loading**

Direction	**Loading**
Longitudinal	3.5g Tensile, 7g Compressive
Lateral	6g Tensile/ Compressive

Table 3 Static Loads

- **Harmonic Loading**
  DA-Displacement Amplitude

	Frequency range(Hz)	**Qualification level**	**Acceptance level**
Longitudinal axis	(i) 5-8	34.5 mm(DA)	23 mm (DA)
	(ii) 10-100	4.5g	3g
Lateral axis	(i) 5-8	34.5 mm(DA)	23 mm(DA)
	(ii) 8-100	3g	2g
Sweep rate	2 oct/min	4 oct/min	

Table 4 Harmonic Vibration Loads

- **Random Loading**

	Qualification	**Acceptance**
Frequency(Hz)	**PSD**(g^2/Hz)	**PSD**(g^2/Hz)
20	0.002	0.001
110	0.002	0.001
250	0.034	0.015
1000	0.034	0.015
2000	0.009	0.004
g RMS	6.7	4.47
Duration	2 min/axis	1 min/axis

Table 5 Random Vibration Loads

C. Thermal Simulations

Some basic simulations have been completed on ANSYS on a simplified model of Sanket to gain the knowledge of thermal analysis and simulations. An algorithm on MATLAB is used to thermally model the orbit [7]. The design process followed for thermal simulations:

- Perform transient thermal simulations on the present Sanket model to check if the electronic components are well within the working range during the course of the orbit.
- Depending on the results of the simulations, devise a thermal control strategy to ensure that the temperature is maintained well within the operational range of the components.

VI. Testing

A. Deployment testing

The deployment testing of the antenna was done on the acrylic prototype of the ADS (ref Fig 2). Initially, the testings were done in order to find the range of voltage/current across the nichrome wire that would ensure the cutting of nylon wire in around two seconds. A 32 AWG nichrome wire of length 1.5 cm was used. Firstly, the antennas were coiled in the C shaped sub-chassis. Then, Nylon thread is passed through Nichrome wire and it's two ends are tied to each PVC sheet holding antenna. The nichrome wire setup was then pulled back through the grooves to bring in some tension in the nylon wire. A digital power source with a range of 0V-29V was used to generate a potential difference between the ends of nichrome wire, however, the test was concluded under 4V.

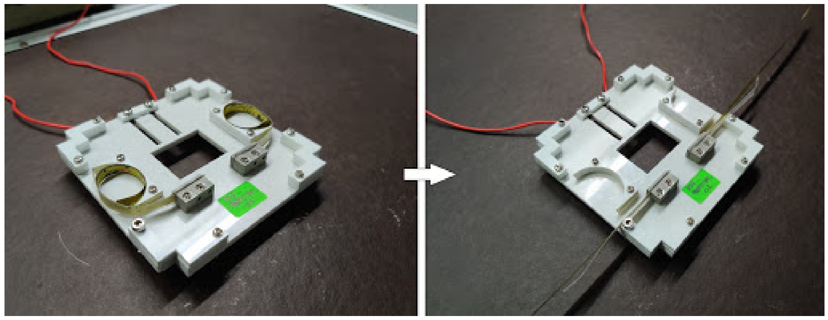


Fig. 8 Deployment Testing

B. Test Plan for Engineering Model

- Deployment Test for ADS module: Functionality and redundancy measures testing of ADS Module under qualification level conditions.
- RF testing for ADS Module: Radiation pattern testing of the deployed antenna.
- Auxiliary system functional testing: Operational modes and redundancy measures testing with a simulated interface from PS4OP.

C. Test Plan for Qualification Model and Flight Model

- Vibration testing: Integrated structure will be tested under critical vibrational frequencies. This test is done before the Thermo-Vacuum test as launch loads are applied before orbital loads in real-life scenarios too.
- Thermo-Vacuum testing: Functional testing of the entire system under orbit simulated loads.
- Shock Testing: The spacecraft experiences mechanical shocks during the liftoff and subsequent launch trajectory. Hence, the satellite is tested by subjecting it to shocks in an controlled environment.

VII. Results

A. Antenna simulation results

Length of poles of dipole antenna for which S11 is minimum in amateur UHF band is 178mm. Poles of antenna are along the 'z-axis'. Following are S11 and 3D polar plots for optimized design. The S11 value of the optimized antenna amateur band is between -31dB and -37dB (Ref Fig. 9). Also, the radiation pattern is highly directive with maximum gain of 4.41dB (Ref Fig. 10). .

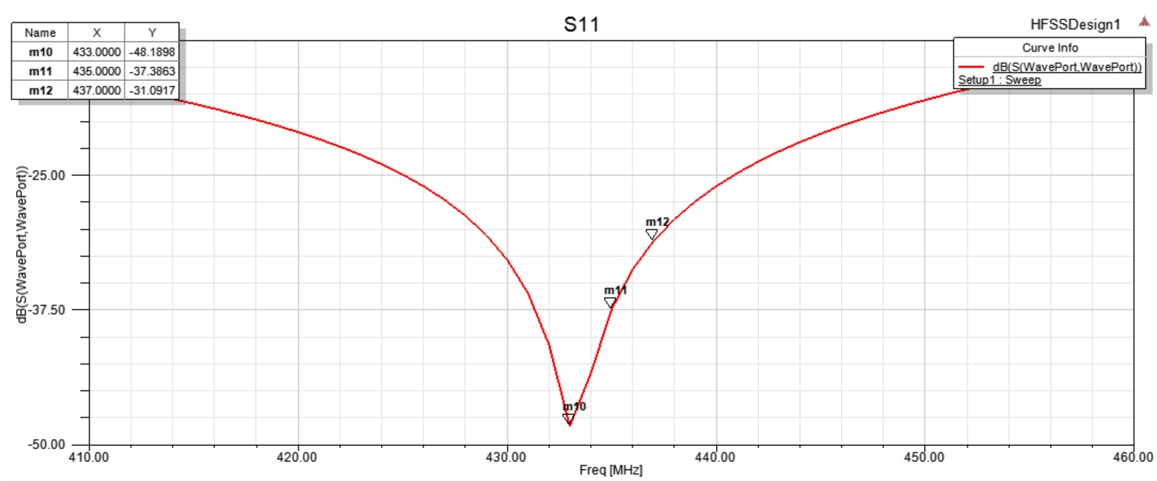


Fig. 9 S11 plot

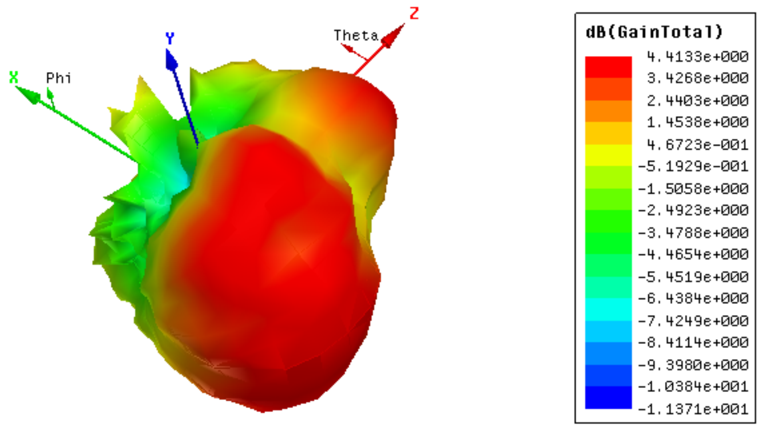


Fig. 10 3D radiation pattern

B. Structural simulation results

In order to investigate the structural safety of Sanket in the launch environment, Equivalent (Von-Mises) (denoted by E) stresses from the static, harmonic, and random analysis are used. The factor of safety (FOS) is calculated for every part of the system from ANSYS simulation results (ref. Table 6). We try to achieve FOS > 1.5.(Ref Fig. 11)

$$Factor\ of\ safety = \frac{Yield\ Stress}{E} \tag{1}$$

	Static (Max. Stress-MPa)	1st Mode Frequency (Hz)	Harmonic (Max. Stress-MPa)	Random Vibration (Max Stress-MPa)in x-axis	Random Vibration (Max Stress-MPa)in y-axis	Random Vibration (Max Stress-MPa)in z-axis
Component (ref Fig 2)	Bottom Cage	PCB	Support Rail	Bottom Cage	Bottom Cage	PCB
Operational Limit	275	90(min.)	275	275	275	120
Simulation Results	11.49	252.76	5.22	29.45	32.18	54.63
Factor of Safety	23.93	-	52.68	9.34	8.55	2.20

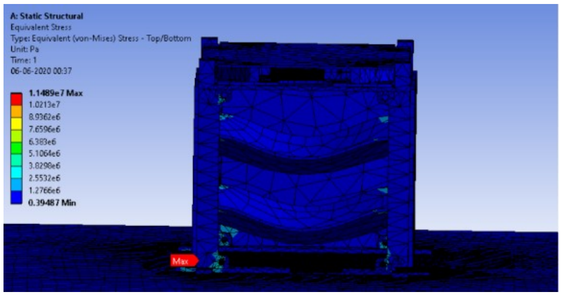
Table 6 Results of Structural Simulation

C. Thermal simulations result

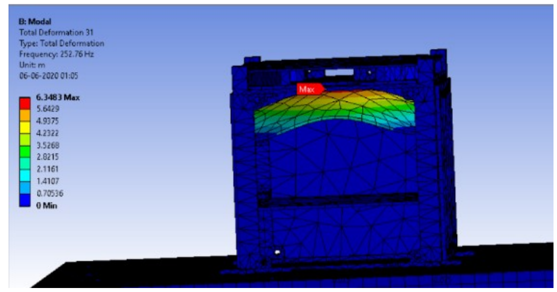
Thermal Simulation Analysis: A simulation on ANSYS was performed on the simplified model for one orbit period. The maximum temperature recorded over the time period was 79.362°C on the C-Shaped sub-chassis. The minimum temperature recorded over the time period was -85.402°C on the antenna.(Ref Fig. 12)

D. Deployment testing results

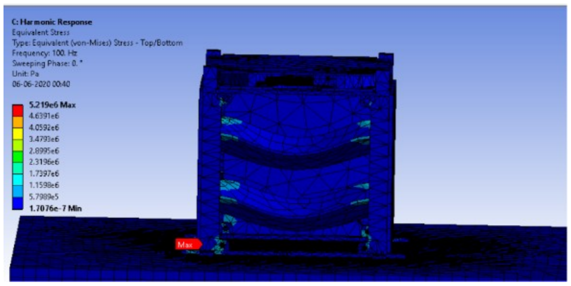
From the testing done at room conditions, it is observed that the time to break the nylon thread is less than 2 seconds when the current in Nichrome is around 1.2 Ampere. At this current, the temperature of Nichrome reaches more than 200°C which is significantly higher than the temperature of PS4-OP. This ensures that, thermal cutting is not initiated automatically, due to expected temperature variations of the system, while PSLV is launched or in orbit.



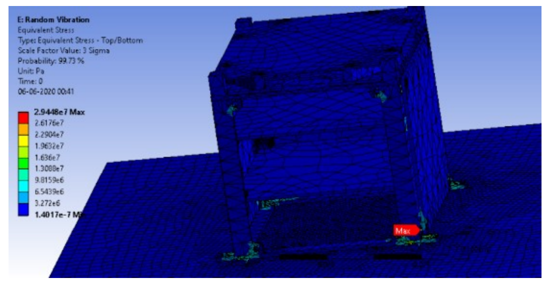
(a) Static Structural Stress levels



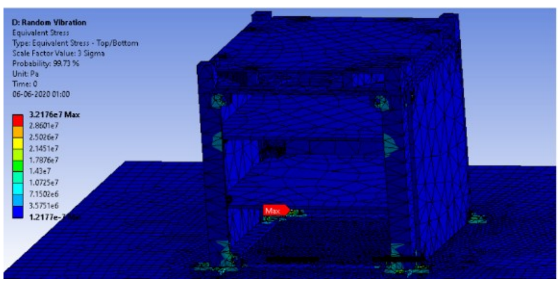
(b) Modal Analysis - 1st mode



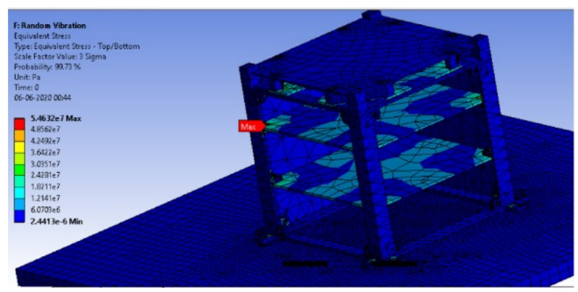
(c) Harmonic Response Analysis



(d) Random Vibration Analysis(x-axis)



(e) Random Vibration Analysis (y-axis)



(f) Random Vibration Analysis (z-axis)

Fig. 11 Simulation results for AUX_001_0008

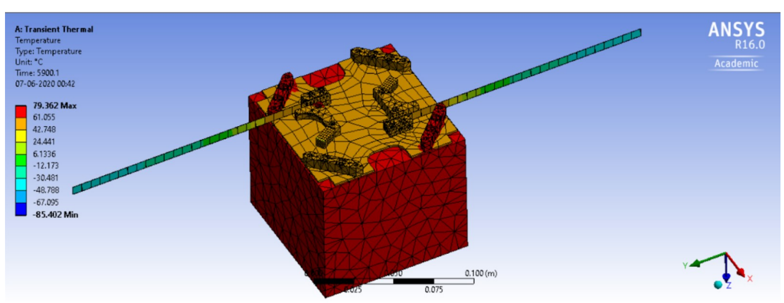


Fig. 12 Temperature on the simplified model of AUX_001_0007 after one orbit period

VIII. Conclusion

Antenna simulations show that the radiation pattern gets highly distorted due to the large metallic body of PS4-OP. The gain of the antenna is significantly higher than the conventional dipole antennas making the radiation pattern directive. This puts the requirement of precise control on the platform for continuous signal reception. Due to the unavailability of anechoic chambers in the amateur UHF band to us, it is decided to measure the radiation pattern in open ground to minimize the inaccuracy due to signal absorption.

The deployment test shows that the deployment time is less than 1 second at room temperature, but it increases as the surrounding temperature decreases. This encourages the necessity of deployment testing at different temperature and pressure conditions. Following this need, a new task of making a vacuum chamber has been started in the team and is expected to be complete in August 2020. The structural simulations indicate that every structural component has FOS > 1.5. Structural design changes keep surfacing as the complete design advances towards completion. It will be intended in the coming time to continue the scrutiny of the structure. More refined thermal simulations are necessary so that we incorporate everything in our thermal model, get more accurate results, and check the system for temperature based failures through these refined simulations.

The mission currently is at the stage where the design is finalized and component level testing is started according to the V-model design approach. It is aimed to have the Engineering Model tested by December 2020. The PS4-OP is an excellent platform for this technology demonstration mission as it provides power, and more importantly the telemetry and telecommand interface. The telemetry will help to closely monitor the system status even if the deployment fails. This gathered data will help in critical analysis of failure, which will aid the design of future missions.

Acknowledgments

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