SANKET

IIT Bombay Student Satellite Project

Preliminary Design Review

Department of Aerospace Engineering,

Indian Institute of Technology, Bombay

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Preface
Sanket Preliminary Design Review

"**Sanket**", literally meaning "signal" in Sanskrit, is the name of the indigenously developed Antenna Deployment System (ADS) which is used to transmit signals from the satellite to the Earth. The Antenna Deployment System has become an essential component of any nano-satellite design due to space constraints during launch. About 20 % of CubeSat missions have failed due to failure in the communication system. Thus, there is a pressing need for a reliable communications system for CubeSats. Various international companies sell ADS but are followed with steep costs and accessibility issues.

Our Antenna Deployment System module is developed as an independent module compatible with standard CubeSat sizes of 1U, 2U, and 3U. We are planning to ground test this technology to TRL-8. Post successful testing, this technology will be transferred to the Indian space industry to promote future CubeSat missions in India.

The team started working on Sanket in August 2019. The requirements were listed down and the system was divided into electrical, commnication and mechanical subsystems. This report gives an insight of the work done on the system until September 2020. It includes all the major decisions taken and the rationales behind them. This report will serve as the building block for further improvements in design.

Acknowledgements

We would first like to extend a special thanks to ISRO small satellite group director Dr SA Kannan for guiding us and a big thank you to the whole ISRO team for inspiring young minds to venture into the domain of space science and engineering. We would thank the entire faculty involved in this project, especially Prof Varun Bhalerao, Prof Prabhu Ramachandran and Prof Arnab Maity, our Faculty Advisers for giving us timely inputs and suggestions as also freedom and space for our design. We extend thanks to IRCC, IIT Bombay for providing us funds needed for a project of this magnitude. We thank Prof Hemendra Arya for his course on System Engineering which has helped us in organising the project well. We wish to thank the Aerospace Department, IIT Bombay for providing us lab space. We would like to thank IIT Bombay as a whole for creating an environment conducive for growth and excellence. We would also like to have this opportunity to thank Pratham and its team for the team culture they had set up and the learnings they passed on to us along with the dream. Finally, we would like to thank the families of our team members who support us.

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Revision No.	**Date**	**Description of Change**	**Pages Affected**
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Chapter 1

Introduction to Sanket

An Antenna Deployment System (ADS) has become an essential component of any pico- or nanosatellite 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), and aims to qualify the team's Antenna Deployment System in Ultra High Frequency (UHF) band 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. The Antenna Deployment System is developed as an independent module that is compatible with typical CubeSat sizes 1U, 2U, and 3U.

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.

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 design approach followed is based on the V-model concept of Systems Engineering. We have broken down the system into three subsystems, namely Communication subsystem, Electrical subsystem, and Mechanical subsystem. Communication subsystem is responsible for transmitting the generated signal, which will be in a form of Morse code, and receiving the uplinked data to Sanket. Electrical subsystem takes care of the power regulation and distribution to the various components of the Sanket.It also serves as the brain of the Sanket and takes decision regarding operation of Sanket based on the Health monitoring data. Mechanical subsystem is responsible for designing the structure of Sanket considering various factors such as launch loads and space environment.

Chapter 2

Communication Subsystem

2.1 Introduction to Communication Subsystem

The communication subsystem is responsible for data exchange between Sanket and the ground station post the antenna deployment. For the payload of Sanket, a two way communication capable system using a single deployable UHF dipole antenna is designed. All the data exchange is differentiated by two distinct signals : Downlink and Uplink. The downlink will contain the signature of Sanket and critical health monitoring (HM) data, and will be transmitted to the ground station in the form of morse code using On-Off Keying (OOK) modulation. The uplink is for data transfer from the ground station to the satellite. Uplink commands will be received by the system as a GFSK modulated wave. Both uplink and downlink will be functional all over the world. The communication subsystem has to design a half-duplex system for the two types of signal - downlink and uplink, while taking in account various requirements on the subsystem.

2.2 Requirements On Communication Subsystem

2.2.1 From Mission

- Design provisions for uplink and downlink for the purpose of testing communication through ADS in flight
- Operate at frequencies which have been assigned to the system by IARU following their guidelines
- Incorporate HM data in provided downlink

2.2.2 From ISRO

- RF frequency, power and sensitivity to be in compliance with PS4OP's RF system requirements

2.2.3 From Electrical Subsystem

- Select components which will work at 3.3 V level

2.2.4 From Mechanical Subsystem

- Size of PCB should be 92mm x 92mm

2.2.5 From Testing Considerations

- Comm link should be testable in thermovac without antennas.
- Provisions should be made to access following peripherals on-demand
    - Downlink
    - Uplink
- Communication components should qualify the environmental test. They should have minimum TID tolerance of 10 krad and work in the temperature range of -40° to 85° Celsius.

2.3 Design of Communication Subsystem

The Design of the onboard communication subsystem is as shown in Figure 2.1. The colour code is as follows :

- Green coloured components are used only during downlink. Cyan coloured components are used only during uplink. Rest all are used during both.
- Purple coloured components are not a part of the communication subsystem and are not present on the communication PCB, rather interfaced with it externally
- The white component is used for interfacing with the antenna deployment system

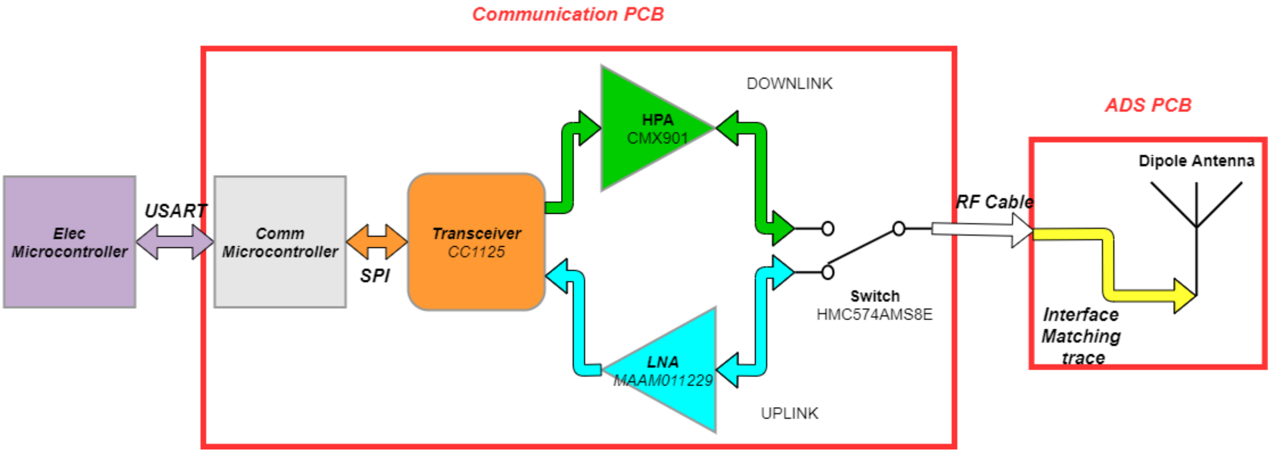


Figure 2.1: Design of communication subsystem

The communication subsystem is designed to establish half-duplex communication in the UHF band using a single dipole antenna. The communication subsystem comprises two PCBs namely, Communication PCB and ADS PCB. The Communication PCB contains the components for amplification, modulation, and demodulation of signal and also for data management and scheduling. The ADS PCB consists of a voltage regulator, nichrome wire and detection switches to check antenna deployment. It also contains the impedance matching circuit and is responsible for the transmission and reception of signals through the dipole antenna.

Function	Component	Max Power Consumption (mW)
Microcontroller	ATmegaS128	40
High Power Amplifier	CMX901	1923
Transceiver	CC1125	168
Low Noise Amplifier	MAAM011229	200
High Power Switch	HMC574AMS8E	0.003

Table 2.1: Components on Communication PCB

Function	Component
Impedance Matching	RF Trace
Antenna	Deployable Dipole

Table 2.2: Communication Components on ADS PCB

All the components work with the supply voltage of 3.3V. The Communication PCB will be designed such that all the components on it are properly accommodated on a board of maximum size 92mm x 92mm. The high power switch on the Communication PCB is linked to the impedance matching trace on the ADS PCB using SMA connectors and RF cable. The microcontroller on the communication PCB is interfaced with the electrical microcontroller using USART protocol. The data to be downlinked is fetched from the electrical microcontroller and transmitted using on-off keying modulation technique. The uplink will receive the commands (Eg. KILL, RESET, TEST) as a GFSK modulated wave. These commands will then be sent to the electrical microcontroller after processing. The communication microcontroller also sends the critical health monitoring data of the components on the communication PCB to the electrical microcontroller through interrupts to store it in EEPROM for further transmission through telemetry. This is covered more in detail in section 2.6 Data Management.

The system is designed to be half-duplex, i.e. the system can transmit and receive but not at the same time. Both uplink and downlink are accommodated on the same antenna by using a high power switch. The HPS will be controlled by the communication microcontroller which in turn can be asked to switch to receive or transmit modes by the electrical microcontroller through interrupts to change operational modes. Both these links will be functional all over the world. The operational modes have been discussed in section 2.7 Flight Code.

A careful procedure was followed for the selection of all components, and detailed testing plans have been laid down. All the design decisions have been mentioned in the sections that follow. The feasibility of the communication subsystem was also checked by the link budgets which are described in more detail in section 2.9 Link Budget.

2.4 Downlink

Downlink will be used to transmit health monitoring data of Sanket to the ground station in the form of morse code and will be functional all over the world. It will be done using OOK modulation @ 435 MHz. The components on the communication PCB used during downlink are microcontroller, CC1125, HPA and HPS (refer Fig 2.1). The selection criteria and detailed testing plans for the components have been listed down in this section.

2.4.1 Modulation

On-Off Keying (OOK) is a type of Amplitude-Shift Keying (ASK) modulation, used to transmit morse code over radio frequencies (also referred to as CW (continuous wave) operation). Morse code is a method to encode text characters as sequences of dots and dashes. OOK has been chosen as the modulation for downlink since it has the best Signal-to-Noise Ratio (SNR) (least required threshold of 10dB) out of all the modulations. The SNR compares the level of the desired signal strength to the level of background noise. The higher the SNR above the required threshold, the better is the reception. Since our mission objective is to check the working of the ADS, the modulation with the least required SNR is used which increases our chances of good signal reception.

2.4.2 Microcontroller

We will be using ATmegaS128 as our communication microcontroller and it has the following specifications:

- 8-bit Microcontroller
- Dual Programmable Serial USARTs
- Space grade
- Tested up to a Total Ionizing Dose of 30 krads(Si)

2.4.3 CC1125

We will be using CC1125 which is a fully integrated single-chip radio transceiver.It has the following specifications:

- Configurable Data Rate : 0 to 200 kbps
- Sensitivity : -110 dBm to -129 dBm
- Maximum TX power : 16 dBm
- Supported Modulation Formats: GFSK, OOK

CC1125 has space heritage. It has been used by previous cubesats missions.

2.4.4 High Power Amplifier

A high power amplifier converts a low power signal into a high power signal. It provides the much required gain to overcome the path loss and other attenuations for receiving a better signal at the ground station.

Selection Criteria

The following parameters were considered during the selection of the high power amplifier:

- Gain : The gain of HPA should be very high and it is the primary parameter considered during the selection process.

- 1dB Compression Point : 1dB compression point is the input power at which the amplifier gets saturated.This power must be significantly higher than our input power.
- Power Consumption : The power consumption must be such that total power consumed by all components lies within the power budget. Also it should also have good power added efficiency.

CMX901 was finally selected based on the parameters mentioned above.

Specifications of CMX901:

- High gain of 42.5dB @435 MHz
- 1dB compression point of -10dBm
- 1.923 W of power consumption at 52% efficiency.

Testing Plan

- **Gain**

  Objective-Measurement of Gain related parameters

  Objective : Measurement of gain related parameters

  Test Setup : Vdd = 3.3V, Vparamp = 3.3V, Input Power = -10dBm, OOK @ 435 MHz

  Procedure : The testing will involve giving an input signal using a signal synthesizer and observing the output on a spectrum analyser. The input frequency will be varied over a small range to check the variation in gain values.

  Expected outputs : Gain = Output Power/Input Power = (42 - 43 dB) Gain response = Gmax - Gmin = (1.5 dB)

- **Power Consumption**

  Objective : Measurement of power consumption

  Test Setup : Vdd = 3.3V, Vparamp = 3.3V, Input Power = -10dBm, OOK @ 435 MHz

  Procedure : The input will be given using a signal generator. Current and gain will be measured using a VNA.It has to be ensured that the gain is at the optimum value.

  Expected outputs : Power consumed = Vdd*I = 3.3*I = (1.8 - 2.1W) where I is the current measured using VNA.

- **1 dB Compression Point**

  Objective : Find the 1dB compression point

  Test Setup : Vdd = 3.3V, Vparamp = 3.3V, OOK @ 435 MHz

  Procedure : The input signal will be given using a signal synthesizer and the output power will be measured using a power meter. The input power will be increased gradually until a change of 2dB in input shows a change of less than 1dB in the output power level.

  Expected outputs : P1dBm (-12 to -10 dBm)

- **S parameters**

  Objective : Measurement of S parameters(both magnitude and angle)

  Test Setup : Vdd = 3.3V, Vparamp = 3.3 V, Input Power= -10dBm

  Procedure : The values of S parameters will be measured using VNA. The input will be given using a signal generator and the outputs observed on VNA.

  Expected outputs : S11(0.859, $\angle$ - 50.154°) to (0.822, $\angle$ - 55.754°)

- **Spurious and Harmonic emissions**

  Unwanted frequencies at the output are called spurious frequencies.These are at non-integer multiples of the input frequency. Harmonic emissions are also unwanted frequencies but these are at integer multiples of input frequency.

  Objective : Spurious and harmonic emission measurements

  Test Setup : Vdd = 3.3V, Vparamp = 3.3 V, Input Power = -10dBm, OOK @ 435 MHz

  Procedure : The input signal is given using a synthesized sweep oscillator and the output is observed on a spectrum analyzer. Excess power levels of unwanted frequencies are noted down.

  Expected outputs : First and second harmonic distortions are expected at - 30dBc and -52dBc respectively, some spurious frequencies may also occur (in dBm)

2.4.5 High Power Switch

A high power switch is a device used to route high frequency signals through different transmission paths. We use a high power switch to route signals through the two, uplink and downlink, transmission paths.

It has three ports RF1, RF2 and RFC (refer the Fig of HPS). For our case, RFC is connected to the RF cable, RF1 is connected to HPA and RF2 is connected to LNA. During downlink we want the signal from the HPA to reach the RF cable without leaking into the LNA, therefore the switch connects RFC and RF1 to complete the downlink transmission path while providing isolation between RF1 and RF2. .Similarly during uplink we want the signal from the RF cable to reach the LNA without leaking into the HPA, so the switch connects RFC and RF2 while providing isolation between RFC and RF1. Isolation is the measure of attenuation of an unwanted signal transmitted from one port to another. High isolation between the ports ensures that no signal leaks into the wrong port.

Selection Criteria

The following parameters were considered during the selection of the high power switch :

- Isolation : As the switch has three ports, we have to consider the three possible isolation values, i.e. between RF1 and RF2 ,RFC and RF1, RFC and RF2. Each of these values must be high.
- Insertion Loss : The insertion loss of a switch should be as low as possible.
-)1dB Compression Point : The P1dB power should be higher than the input power given to the switch.

HMC574A was finally selected based on the parameters above.

Specifications of HMC574A :

- It has a high isolation of 30dB between all three ports namely RFC, RF1 and RF2.
- A low insertion loss of 0.25 dB.
- High enough P1dB of 34 dBm.

Testing Plan

- **Insertion Loss**

  Objective : Insertion Loss measurement

  Procedure : Input of a fixed power will be given to the switch and the output power will be measured using the spectrum analyzer.The ratio of output power and input power will give the insertion loss.

  Expected outputs : Insertion Loss (0.2 to 0.3 dBm)

- **Isolation**

  Objective : To find the isolation between ports RFC, RF1 and RF2

  Procedure : Input of fixed power will be given to the switch and the power level at the port where we don't want an output will be measured using a spectrum analyzer. The attenuation of the input signal at this port is the isolation between the two ports.

  Expected outputs : 30dBm for all three isolation values.

- **1 dB Compression Point**

  Objective : To Find the 1dB compression point

  Procedure : The input signal will be given using a signal synthesizer and the output power will be measured using a power meter.The input power will be increased gradually until a change of 2dB in input shows a change of less than 1dB in the output power level.

  Expected outputs : P1dBm (34 to 38 dBm)

2.4.6 Selection b/w HPS and Circulator

An alternative to HPS was mentioned in 'Learnings from Pratham' as the circulator. RF circulator is a three-port ferromagnetic passive device used to control the direction of signal flow in a circuit. It provides two types of isolation similar to a high power switch. But, we will not be using a circulator for Sanket due to following reasons :

- Large dimensions - Coaxial circulators have dimensions of 50mm*50mm whereas surface mount are around 25mm*25mm big.
- Very large weights - The coaxial circulators are available in military-grade but the weight is 140 g. SMT circulators which are much smaller than coaxial ones also weigh around 30g.
- Any presence of a strong magnetic field around the product can reduce efficiency.

These above specifications of circulators and its handling was discussed with Caroline Yao, a representative of uiy.com. The isolation provided by the SMT circulators is not more than that provided by a high power switch, so we have decided to use HPS for Sanket.

2.5 Uplink

Uplink is the communication from the ground station to the satellite. Uplink will be used to transmit certain commands, such as KILL, RESET and TEST, to the satellite. RESET command will change the operational mode to RESTART in which system sequentially switches everything off and then switches everything on. KILL command will be used to change the operational mode to KILL in which the system sequentially switches everything off. TEST will be a known signal whose feedback will be taken in telemetry and downlink to verify the uplink. It will be done using GFSK modulation @ 435 MHz. The components playing an active role in uplink are Antenna, HPS, LNA, CC1125 and microcontroller, all of which are used during downlink as well except LNA. (refer Fig 2.1)

2.5.1 Modulation

After benchmarking the data of modulation methods used by satellites, GFSK has been decided for uplink modulation as it can be used at higher data rates with a better noise immunity and moderate SNR requirement. Gaussian Frequency-Shift Keying (GFSK) is a digital modulation technique which reduces the spectral width of the signal thus attenuating the noise. Audio Frequency Shift Keying (AFSK) has a high requirement of SNR and is not always used for high-speed data communications, since it is far less efficient in both power and bandwidth than most other modulation modes. FM and OOK have low data transmission rates and are not used frequently for uplink purposes to cubesats. Moreover, the knowledge of using GFSK exists in the team as this modulation technique was used for uplink in Pratham.

2.5.2 Low Noise Amplifier

A low noise amplifier converts a low power signal to a high power signal without significantly degrading its signal-to-noise ratio. It is used in uplink to amplify the received signal which has very low power owing to the large distance it has travelled. If the amplifier used introduces some additional noise, the already low SNR of the received signal will degrade further and this will make its demodulation very difficult .Hence, a low noise amplifier is a crucial component in the system.

Selection criteria

A low noise amplifier was to be selected considering the following parameters:

- Gain : The gain of a LNA should be high as the power level of the received signal is very low.

- 1dB Compression Point : 1dB compression point is the input power at which the amplifier gets saturated. This power must be significantly higher than our input power.
- Noise Figure : The LNA should have a very low noise figure, that is it should not add a lot of noise and maintain the SNR while amplification.

MAAM011229 was selected considering the above parameters.

Specifications of MAAM011229:

- It has a high gain of 19dB
- It has a low noise figure of 1.3 dB
- It also has a high 1dB compression point of 17dBm

Testing Plan

- **Gain**

  Objective : Measurement of gain related parameters

  Input Signal : GFSK @ 435 MHz

  Procedure : The testing will involve giving an input signal using a signal synthesizer and observing the output on a spectrum analyser.The input frequency will be varied over a small range to check the variation in gain values.

  Expected outputs : Gain = Output Power/Input Power = (19dB) Gain response = Gmax - Gmin

- **Spurious emissions and Harmonics**

  Objective : Spurious and harmonics measurements

  Input Signal : GFSK @ 435 MHz

  Procedure : The input signal is given using a synthesized sweep oscillator and the output is observed on a spectrum analyzer. Excess power levels are unwanted frequencies, which are noted down.

  Test outputs : First and second harmonic distortions are expected at –dBc and –dBc respectively, some spurious frequencies may also occur (in dBm)

- **Power**

Objective : Measurement of Power consumption

Input Signal : GFSK @ 435 MHz

Procedure : The Input will be given using a signal generator. Current and gain will be measured using a VNA. It has to be ensured that the gain is at the optimum value.

Expected outputs : Power consumed = Vdd*I = 3.3*I = (0.2W) where I is the current measured using VNA.

- **Noise figure**

Objective : Measurement of noise figure

Input Signal : GFSK @ 435 MHz

Procedure : The measurement will be carried out using a noise figure meter. First,the meter is calibrated using a noise source and then the LNA is inserted in the path to find the noise figure.

Expected outputs : Noise figure(1 to 1.5 dB)

2.6 Data Management

2.6.1 Downlink data

Comm microcontroller will receive Health Monitoring (HM) data of the whole system from Elec microcontroller for the purpose of downlink. The HM data will be preprocessed by Comm microcontroller before sending it to CC1125 for OOK modulation. For preprocessing, the following methods are being considered-

Data through morse code encoding

1) Conversion to T and E
The 1s and 0s will be converted to T and E respectively. 3 units will be used for T(dash), 1 unit for E(dot) and 3 units for the spaces in between each symbol. The average time taken for transmission in this method was calculated over 100 data points (each of one byte size). It was found that for T and E conversion the average was 35 dot units. The data size required to store in the buffer after conversion to T and E for 100 bits will be 100 bytes.

2) Conversion to hexadecimal values
The binary data will be converted to hexadecimal values. 3 units will be used for a dash, 1 unit for dot, 3 units for space between two hex symbols and 1 unit for space within a hex symbol. The average time taken for transmission in this method was calculated over 100 data points (each of one byte size). It was found that for hexadecimal conversion, the average

was around 26 dot units. The data size required to store in the buffer after conversion to hexadecimals for 100 bits will be 25 bytes.

3) No encoding
If no encoding is done by CC1125, then the transmission will be done bit-by-bit where one symbol corresponds to one bit. In this method we require 1 unit for each symbol and 1 unit for space between consecutive symbols. Time taken for transmitting one byte will be 16 units. The data size required to store in the buffer after conversion for 100 bits will be 12.5 bytes.

The final decision regarding which method is to be used has not been made yet. The preprocessing will also include placing predefined markers in the downlink data. In the cases where some bits are lost while receiving the downlink, these markers will help us identify from where the data is beginning again.

2.6.2 Uplink data

The GFSK modulated uplink signal received will be demodulated by the transceiver and the Comm microcontroller will process it further. If any command (RESET, KILL etc) is found four times continuously in the uplink data, then that command will be sent to Elec microcontroller.

2.6.3 Health Monitoring data

The Comm microcontroller will collect HM data from several components present on the Communication PCB and send it to Elec microcontroller for storage on the EEPROM. The breakdown of the HM data is listed in table 2.3 and pin usage of Comm microcontroller is listed in table 2.4 given below.

Data Type	**No. of Bits**	**Protocol/Interface**
Temperature from thermistor: HPA, LNA	16	ADC
Current sensors: HPA, LNA	16	ADC
Status of transceiver	3	SPI
Temperature of transceiver	8	ADC

Table 2.3: Comm HM Data

Pin Description	No. of Pins
USART(for elec microcontroller)	4
SPI(for transceiver)	4
ADC(for thermistors and current sensors)	5
GPIO(for controlling LNA, HPA, HPS)	6

Table 2.4: Pin Usage of Comm microcontroller

2.7 Flight Code

The Comm microcontroller is always powered up along with the Elec microcontroller. The rest of the components on the Communication PCB will be powered on in the Post-Antenna Deployment Mode. The task of Comm microcontroller is to run in a loop of checking its operational mode and following the defined set of instructions for that mode along with collecting HM data from Communication PCB after certain intervals of time. A complete flow diagram is explained in Fig 2.1.

2.7.1 Nominal Transmit Modes

Nominal Idle Mode

Comm microcontroller will remain idle in this mode. The HPA and LNA will also be in turned off mode hence not using any power in this mode.

Nominal Downlink Mode

Comm microcontroller will receive HM data from Elec microcontroller and preprocess the data. After that, Comm microcontroller will switch the HPS for downlink transmission, turn on HPA and put CC1125 in transmit mode and then send the preprocessed data to CC1125. Comm microcontroller will check the transmit buffer of CC1125 after nearly around 35 seconds. Maximum amount of time will be required when using T and E encoding for downlink (refer section 2.6.1) which is around 35 seconds (the value is tentative and exact value will be decided later based on scheduling), then Comm microcontroller will flip HPS back to the uplink channel, turn off the HPA and put CC1125 in standby mode.

Nominal Uplink Mode

Comm microcontroller will turn on LNA and put CC1125 in receive mode in order to receive uplink data. Then Comm microcontroller will check the receive buffer of CC1125 after nearly around 15 seconds (the value is tentative and exact value will be decided later based on scheduling) and collect the uplinked data from CC1125. After that Comm microcontroller will turn off LNA and put CC1125 in standby mode. Finally the Comm microcontroller will process the data collected from CC1125. If any command (RESET, KILL etc) is found four times continuously in the uplink data, then that command will be sent to Elec microcontroller.

2.7.2 Interrupts

As decided till now, the Comm microcontroller will only be using USART interrupts (for communication with Elec microcontroller). Two types of interrupts will be generated on Comm microcontroller as mentioned below

Operational mode

The Elec microcontroller will send operational mode to the Comm microcontroller. After receiving the operational mode through USART protocol, the USART receive complete interrupt will be generated which will force the Comm microcontroller to change its operational mode (uplink, downlink and idle) accordingly.

HM Data

Elec microcontroller will request HM data of communication PCB from Comm microcontroller by generating USART interrupt on Comm microcontroller. The Comm microcontroller will collect HM data of components on Communication PCB and send it to Elec microcontroller.

2.8 Antenna

2.8.1 Introduction

We will be using a deployable dipole antenna on our cubesat. Tape spring (stainless steel) will be used as a pole for the dipole antenna because of its ability to regain its shape and straighten out.

2.8.2 Antenna Type

We will be using a dipole antenna. Dipole and monopole antennas are previously used on nano satellites. In order to tackle the space constraints, it was decided to use deployable

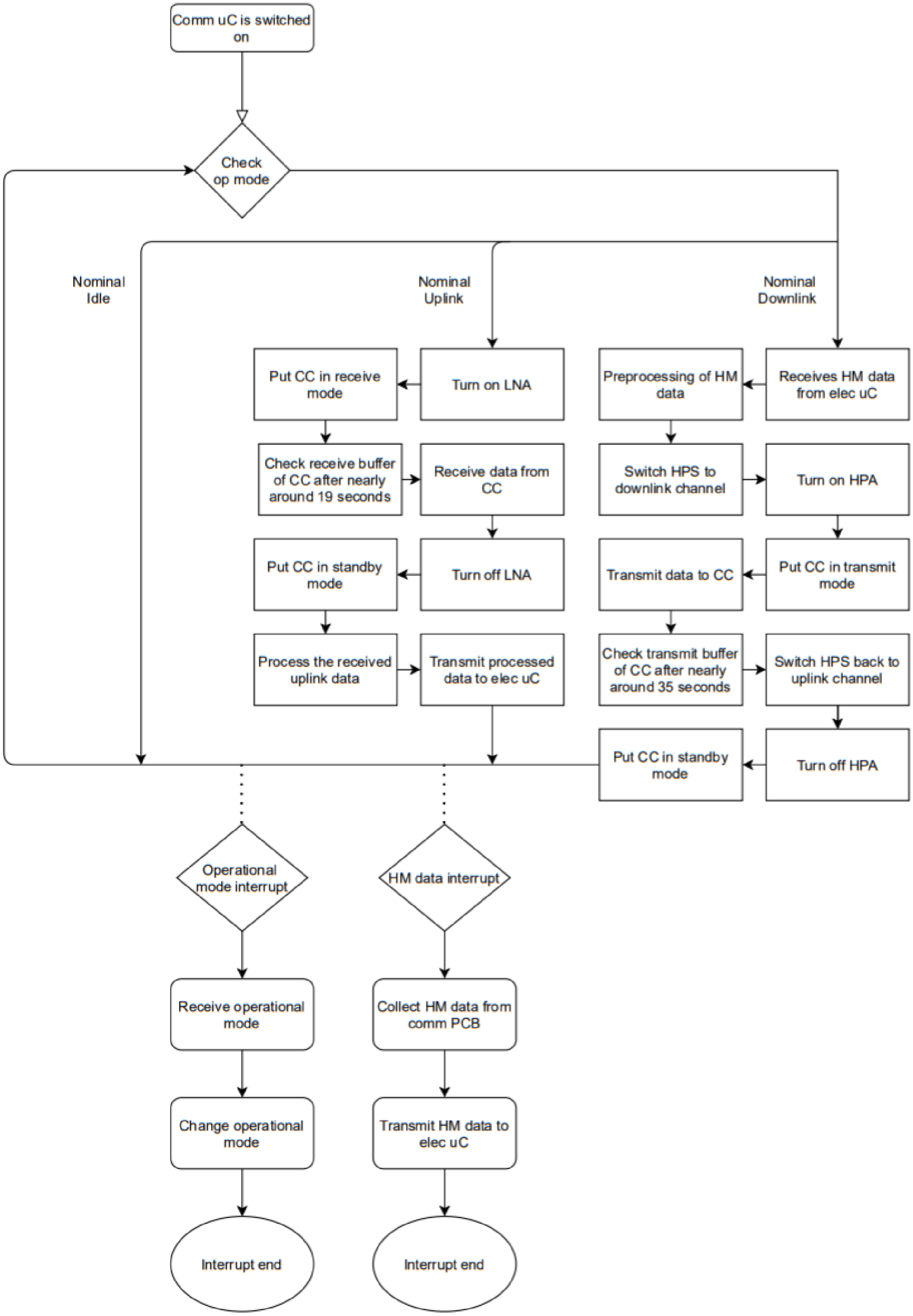


Figure 2.2: Communication Flow Diagram

dipole antennas. Also, the radiation pattern of dipole antennas is symmetric about the axis along the poles and so it is omnidirectional. This means that the radiation from the antenna is not directed and it is spread across a wider area. Although it gives comparatively lesser gain, it ensures that the signal will be received over a higher area on earth. In other words, we can receive and send signals for passes with low maximum elevation too.

2.8.3 Frequency Band Selection

We will be using the UHF amateur radio band range (435 MHz - 438 MHz). The benefit of using the UHF band is that it requires small antenna pole length and hence is ideal for cubesat use. We also relied on benchmarking (benchmarking data can be found in this sheet) as comparatively a larger proportion of the previous student missions have also used this frequency range.

2.8.4 Simulation

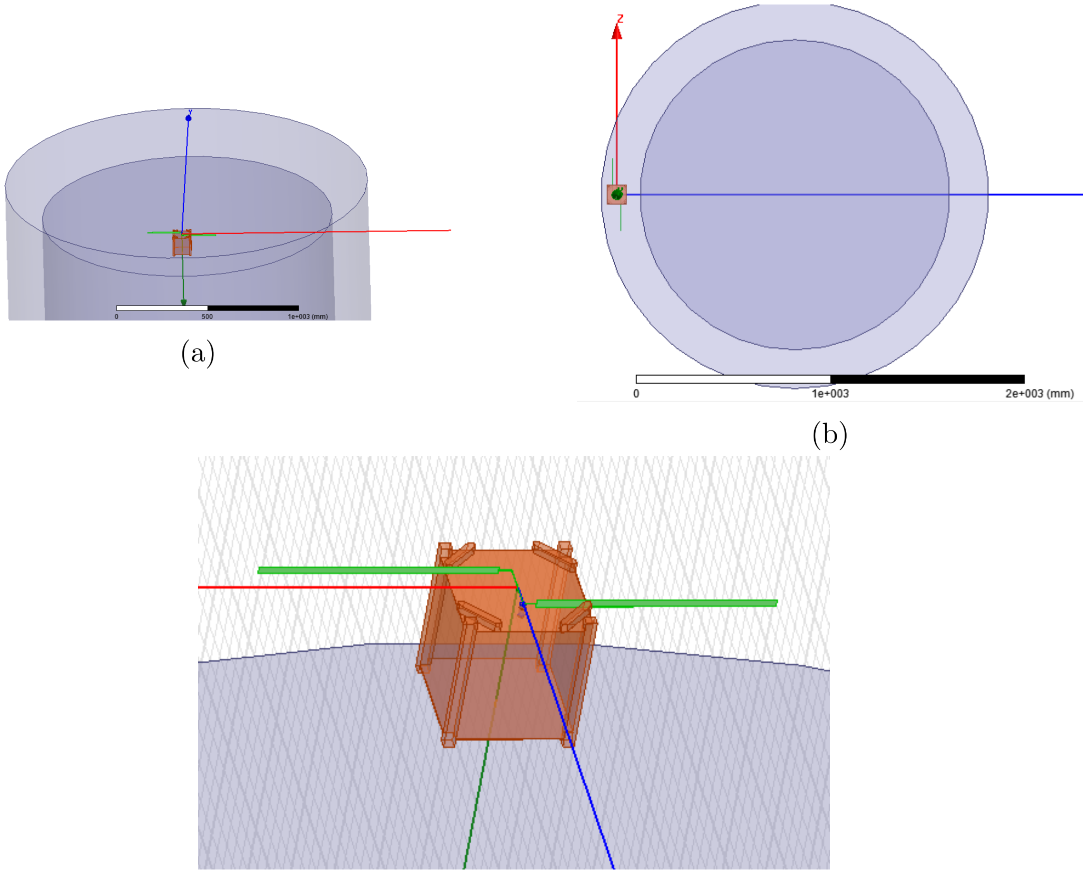
We rely on simulation as not all calculations/ideas can be tested practically. PS4-OP being metallic affects antenna radiations significantly. Simulation softwares give us a reasonable prediction about the characteristics of antenna radiation and return losses. Our cubesat has been simulated on ANSYS HFSS 15.

2.8.5 Modelling

PS4-OP is modelled as a hollow aluminium cylinder with outer diameter of 2 meters, inner diameter of 1.6 meters, height of 2 meters, inner height of 1.6 meters. CubeSat is modelled as a 1U hollow aluminium box. Poles of dipole antenna are modelled as metal strips with variable length (to be optimized), width 6 mm and thickness 0.1 mm. It is placed on top of the cubesat. Cubesat is placed on the edge of flat surface of cylinder (PS4-OP) which closely resembles the actual placement of cubesat on PS4-OP (See Figure 2.3a Figure 2.3b Figure 2.3c).

The PS4-OP's axis lies along its velocity in orbit. We assume that it is 3-axis stabilised and controlled. Here, we had to choose between 3 arrangements. First, cubesat be placed on the center; second, cubesat be placed at an edge - with the antenna along the radius and perpendicular to the radius of circular face of PS4-OP; and third, cubesat be placed at the center of the circular flat face of PS4-OP. As the simulation results suggested, we opted for placing the antenna on the edge towards Earth, with the antenna poles perpendicular to the radius of PS4-OP's surface.

The velocity of the PS4-OP is towards -ve X direction and the Earth is towards -ve Y direction.



(a) (b) (c)

Figure 2.3: Cubesat modeled on PS4-OP

2.8.6 Results

A detailed spreadsheet about the results can be found here. Refer Table 2.5 for results of antenna pole length simulations, Figure 2.4 and Figure 2.5 for S11 plot and Radiation pattern obtained for the antenna :

The S11 obtained at 437 MHz is **-28.4717 dB**.

The radiation pattern, as seen in Figure 2.5 is skewed towards one side with maximum **gain = 4.5744 dB**. This was observed because for our dipole antennas, one pole is the feed pole and one pole is grounded. The PS4-OP is a large metal body in the vicinity of the cubesat and it is considered to be at ground potential. This affects the radiation pattern of the system causing the radiation pattern to be skewed towards the feed pole.

Pole Length (mm)	S11 at 437 MHz (dB)	Freq of Min S11 (MHz)	Min S11 (dB)	Max Gain (dB)	Half Power Beam Width (degrees)	Radiation Pattern Skewed Towards	Pole Closer to PS4-OP's center
178	-18.997	455	-40.8	4.413	74.0385	Left	Feed
180	-18.827	456	-31.8	4.454	75.4583	Left	Feed
182	-23.384	447	-40.3	4.47	73.5278	Left	Feed
184	-28.472	442	-34.9	4.574	72.4698	Left	Feed
185	-20.444	427	-22.0	4.612	73.2043	Left	Feed
186	-25.409	432	-26.7	4.487	75.235	Left	Feed
188	-17.138	416	-30.5	5.17	66.8569	Left	Feed
190	-23.36	430	-25.6	4.756	71.2913	Left	Feed
180	-18.789	456	-24.6	4.598	64.4558	Right	Ground
182	-21.577	451	-32.9	4.814	66.7939	Right	Ground
184	-19.926	450	-23.1	4.842	69.7978	Right	Ground
186	-30.439	436	-30.7	5.123	60.0284	Right	Ground
188	-22.556	426	-25.4	5.104	60.0132	Right	Ground
190	-20.966	429	-21.9	4.924	65.9224	Right	Ground

Table 2.5: Antenna Pole Length Simulation Results

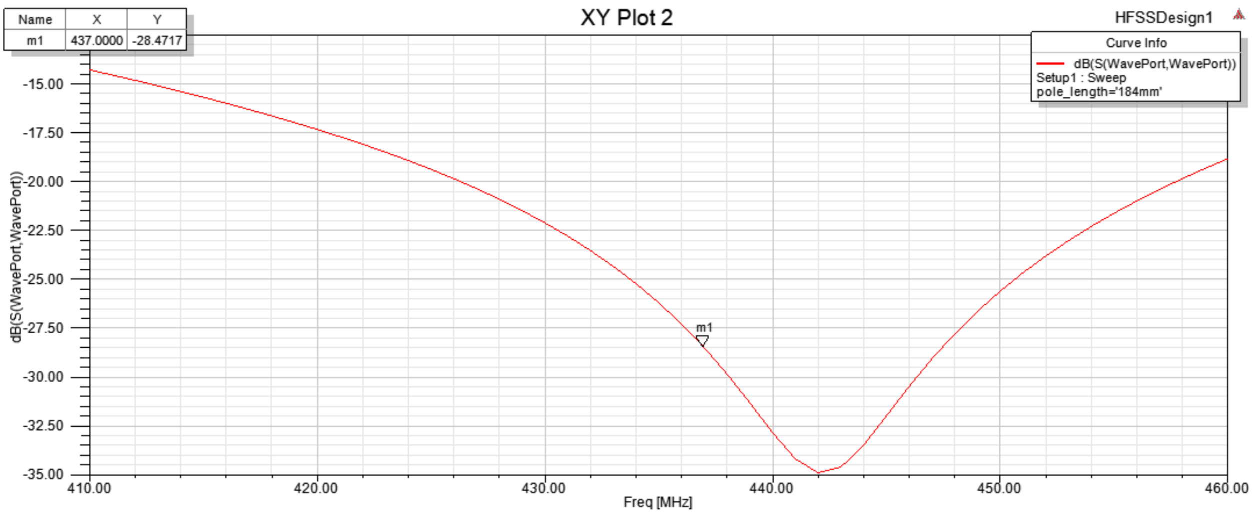


Figure 2.4: S11

2.8.7 Conclusions

As suggested by simulation results, we got the highest gain towards Earth in the orientation with the cubesat placed on the edge of PS4-OP closer to Earth with antenna poles tangential to the circular flat surface of PS4-OP. The best radiation and S11 plot was obtained for antenna **pole length = 184 mm.**

In future, as and when we receive more information about the structure of PS4-OP, we will

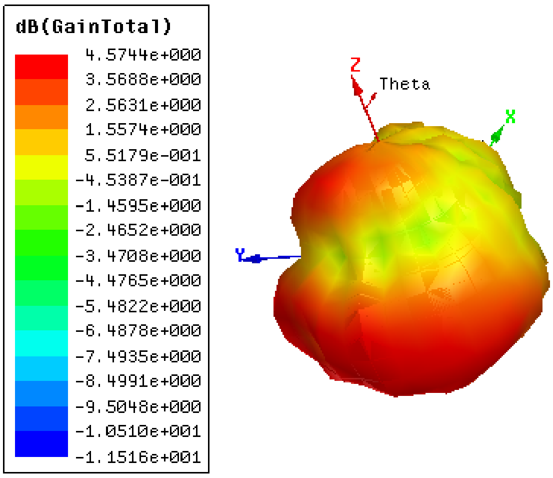


Figure 2.5: Radiation Pattern

model the cubesat on that and re-run the simulations.

2.8.8 Impedance Matching

Impedance matching RF trace present on the ADS PCB is used to connect the antenna to the feed by ensuring maximum power transfer. The communication subsystem is designed at 50 ohm impedance so the antenna impedance of 77 ohm had to be matched with it. The trace widths at both ends of the RF trace, one interfaced with antenna and other with SMA connector, were calculated using Saturn PCB toolkit. These both ends were then linearly interpolated to form a complete trapezoidal trace on the PCB.

2.9 Link Budget

A Link Budget for a satellite mission consists of analyzing the losses in signal power during transmission to study the fraction of transmitted power available at the receiver system. While making the Link Budget, we make sure that an adequate signal power is received in the worst cases for most of the parameters concerned.

This analysis is majorly done by two methods:

- Eb/No method - Ratio of Energy per Bit (Eb) to the Spectral Noise (No)
- SNR method - Ratio of Signal power (S) to the Noise power (N)

The Eb/No method is only applicable where digital modes are used since it requires the energy for each bit to be calculated. Since our downlink is OOK modulated, we can only judge the signal by it's SNR margin. The SNR method is also required to calculate the maximum allowed data rates for digital modes. For our uplink which is GFSK modulated, we have calculated both the margins as it is a digital modulation technique.

2.9.1 Common Parameters

Parameter	**Value**	**Unit**
Orbit		
Apogee Height	450	km
Perigee Height	450	km
Elevation Angle	5	degree
Slant Range	1944.47	km
Path Loss	151.04	dB
Antenna Parameters		
at Spacecraft	dipole(ADS)	
Max Gain	2.7	dB
Beamwidth	68	degree
at GS	yagi	
Max Gain	13	dB
Beamwidth	44.8	
Pointing Loss		
at GS		
Pointing Error	5	degree
Loss	0.14	dB
Spacecraft		
Pointing Error	0	degree
Loss	0	dB
Antenna Polarization Loss	3.01	dB
Atmospheric Gas Loss	2.1	dB
Rain Loss	0	dB
Ionosphere Loss	1	dB

Table 2.6: Common Parameters

2.9.2 Downlink

Parameter	**Value**	**Unit**
Transmitter		
Transmit Power at HPA output	1	W
Line Loss	0.3	dB

Connector Loss	0.2	dB
Antenna Mismatch Loss	0.04	dB
Total Line Loss	0.54	dB
Power Delivered to Antenna	29.46	dBm
Receiver		
Receiver Line Loss	1.6	dB
Connector Loss	0.2	dB
Transmission Line Coefficient	0.66	
Antenna Temperature	500	K
Ground Station Temperature	300	K
lna Temperature	21.5	K
Glna	21.9	dB
TS2000 Noise Temperature	0	K
System Noise Temperature:	453.63	K
SNR Method		
Ground station Effective Noise Temperature:	453.63	K
Ground station Figure of Merrit (G/T):	-15.36	dB/K
Signal Power at Ground stationLNA Input:	-114.17	dBm
Ground station Receiver Bandwidth:	20,000	Hz
Ground station Receiver Noise Power (Pn = kTB)	-142.26	dBm
Signal-to-Noise Power Ratio at G.S. Rcvr:	28.09	dB
Analog or Digital System Required S/N:	10	dB
SENSITIVITY MARGIN	**18.09**	**dB**

Table 2.7: Downlink Budget

Remarks:

- The signal to noise power at the ground station is 28.1 db which is sufficiently high.
- The system required signal to noise ratio of 10 dB comes from our receiver, TS2000 specifications, leading to an adequately high sensitivity margin of 18.1 dB.

2.9.3 Uplink

Parameter	**Value**	**Unit**
Transmitter		
Transmitter Power at HPA Output	10	W
Line Loss	1.3	dB
Connector Loss	0.2	dB
Antenna Mismatch Loss	0.04	dB
High Power Switch Loss	0.3	dB
Total Line Loss	1.84	dB
Power Delivered to Antenna	38.16	dBm
Receiver		
Line Loss + Switch Insertion Loss	0.3	dB
Connector Loss	0.1	dB
Transmission Line Coefficient	0.91	
Antenna Temperature	290	K
Spacecraft Temperature	70	K
LNA Temperature	75	K
Glna	19	dB
CC1125 Noise Temperature	360	K
System Noise Temperature:	350.17	K
Eb/No Method		
Modulation	non-coherent fsk	
BER	1.00E-04	
Eb/No threshold	13.9	dB
Ground Station EIRP:	51.16	dBm
Isotropic Signal Level at Spacecraft:	-105.83	dBm
Spacecraft Effective Noise Temperature:	364.58	K
Spacecraft Figure of Merit (G/T):	-23.14	dB/K
S/C Signal-to-Noise Power Density (S/No):	69.62	dBHz
System Desired Data Rate:	9600	bps
System Desired Data Rate In dBHz:	39.82	dBHz
Command System Eb/No:	29.80	dB

SENSITIVITY MARGIN(Eb/No method)	**15.72**	**dB**
SNR Method		
Spacecraft Effective Noise Temperature:	350.17	K
Spacecraft Figure of Merit (G/T):	-23.14	dB/K
Signal Power at Spacecraft LNA Input:	-103.53	dBm
Spacecraft Receiver Bandwidth:	250000	Hz
Spacecraft Receiver Noise Power (Pn = kTB)	-119.17	dBm
Signal-to-Noise Power Ratio at spacecraft Rcvr:	15.64	dB
Receiver Sensitivity of CC 1125	-110	dbm
Analog or Digital System Required S/N:	9.17	dB
SENSITIVITY MARGIN(SNR method)	**6.46**	**dB**

Table 2.8: Uplink Budget

Remarks:

- The threshold Eb/No for a bit error rate of 10-4 is 13.9 dB.
- The system has a sufficiently large link margin of 15.9 dB at a data rate of 9.6 kbps.
- The receiver sensitivity of cc 1125 is taken to be -110 dBm at considering the worst case scenario (It may range from -129 dBm (300 bps) to -110 dBm (50 kbps)).
- The sensitivity margin obtained using the current specifications is 6.5 dB.

Issues Faced during budget analysis:

- **Choosing the angle to be taken for pointing loss:** Since the PS4OP is three axis stabilized, we assumed that there is a fixed plane attached to the platform which is perpendicular to its flat surface and always passes through the center of the Earth. We chose the angle for the gain such that the pointing loss can be taken to be zero.

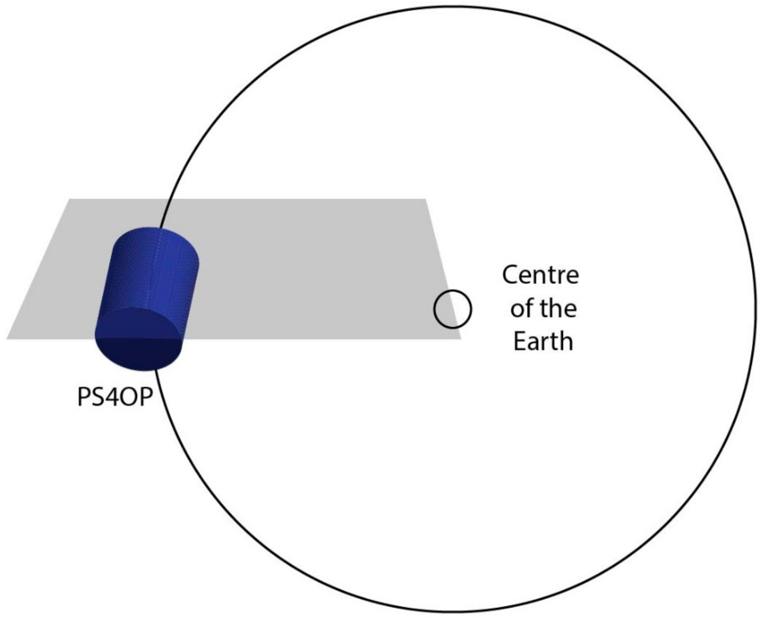


Figure 2.6: The fixed plane

- **Gain of the antenna:** We have taken the mid value of the best and the worst gain possible under the previous assumption with a overhead pass.
- **Antenna temperature:**Antenna temperature is a measure of the noise produced by an antenna in a given environment. We found conflicting resources for antenna temperature, some use really high values considering the impact of the some and some use weighted average of temperatures over the solid angle.
- **Losses due to rain:** It is difficult to accurately calculate the loss caused by rain.

Chapter 3

Electrical Subsystem

3.1 Introduction to Electrical Subsystem

The electrical subsystem is responsible for data management, power management, and operating the ADS PCB to deploy the antennas.

The system receives power from PS4-OP which is restricted to 10W. Our system ensures this power bound is maintained and always consumes power <10W. The power received is brought down to required operating voltage of the system by using voltage regulators and the high frequency fluctuations are removed using an EMI filter. Current limiters are used to put a bound to the flow of current in the system to protect the system from over-current. MIL grade components have been selected for the power regulation and onboard processing

EEPROM on the Elec PCB is used to store the Health Monitoring (HM) data and current configuration of the system to re-configure itself into the intended configuration. Telecommand from PS4-OP to elec microcontroller will be used for configuring the system in orbit as well as to Kill or Reset the system. Apart from these, the Elec microcontroller would also be sending the HM data comm microcontroller for beacon and receive uplink data in a cyclic manner. All the data management would be happening in accordance with the operational modes defined at the system level.

The electrical subsystem is characterized by 2 PCBs that are the AUX PCB and the ADS PCB. The AUX PCB is responsible tasks like power management and data management and the ADS PCB is responsible for the antenna deployment mechanism.

3.2 Requirements On Electrical Subsystem

3.2.1 From Mission

1. System should meet power requirements for 1U, 2U, 3U cubesats
2. System shall operate on 28 V RAW power bus
3. Develop a burn wire mechanism for deployment of antenna

4. Burner circuit should be repeatedly testable. Nichrome wire interface should be made to facilitate repeated testing and electrical interface(pins) should be available for testing
5. Components and PCB should survive the space environment. MIL grade components to be used
6. Develop an algorithm for reliable deployment. Algorithm of the deployment should be such that the deployment happens before "X" attempts.

3.2.2 From Communication Subsystem

1. PCB traces should not interfere with RF signal

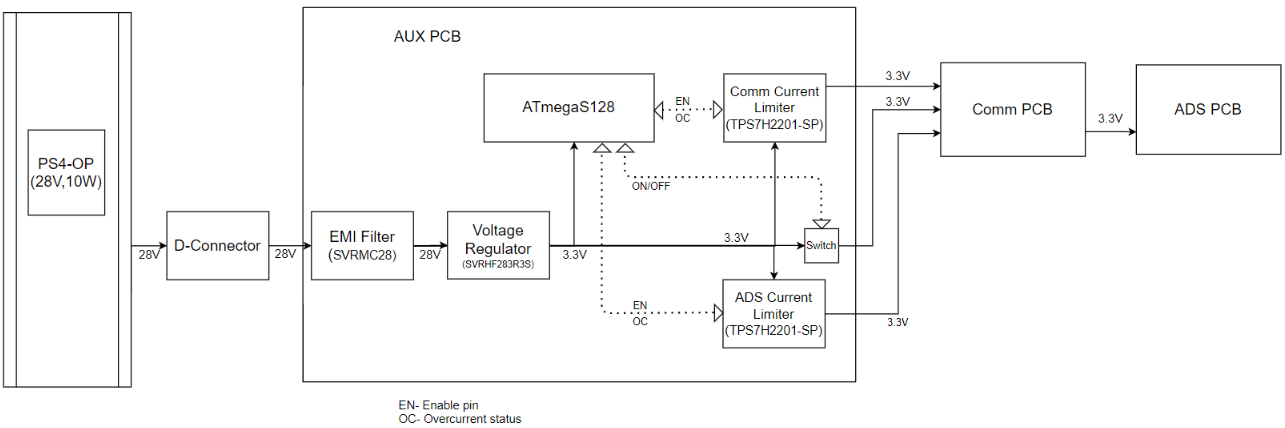
3.2.3 From Mechanical Subsystem

1. Size of electrical components and PCBs should be compatible with mechanical design
2. Nichrome wire should not thermally damage any component

3.3 Power Management

3.3.1 Introduction

Power management comprises interfacing with the PS4-OP to take 28V raw unregulated power input, reducing electrical fluctuations, bringing down the voltage to the desired level, limiting the current and then distributing the regulated power to various components of the system. The AUX PCB is responsible for power management.



3.3.2 Power Budget

Power budget is the calculation of net power consumed by a system at a point of time. The power consumed can vary according to mode of operation. The power consumed by the system is calculated by adding the power consumption of the individual components . There are two ways to calculate power consumed by components. Depending on the component, one of these ways is used to calculate the power consumed:

- By multiplying the current consumed by the component with the operating voltage of the component.
- The power efficiency of the component can be used to gauge its power consumption.

Datasheet of the components is used to check these parameters. Based on components which are ON at a particular moment], we consider three different modes of operations : Deployment of antenna, uplink communication after deployment and downlink communication after deployment. The other operational modes consume significantly less power than these modes.

Components	Quantity	Max Power Consumed (mW)
SVRMC28 (EMI filter)	1	2400
SVRHF283R3S (Voltage Regulator)	1	2508
ATmegaS128	1	40
TPS7H2201-SP (Current Limiter)	1	450
AT69170F (EEPROM)	1	72
TPS-50601A-SP (Voltage Regulator)	1	453
Nichrome wire	1	2000
TOTAL		**7923**

Table 3.1: Power budget during deployment

Components	Quantity	Max Power Consumed (mW)
SVRMC28 (EMI filter)	1	2400
SVRHF283R3S (Voltage Regulator)	1	2508
ATmegaS128	2	80
TPS7H2201-SP (Current Limiter)	1	450
CC1125 (Transceiver)	1	168
AT69170F (EEPROM)	1	72
CMX901 (HPA)	1	2161
TOTAL		**7839**

Table 3.2: Power budget after deployment: Downlink

Components	Quantity	Max Power Consumed (mW)
SVRMC28 (EMI filter)	1	2400
SVRHF283R3S (Voltage Regulator)	1	2508
ATmegaS128	2	80
TPS7H2201-SP (Current Limiter)	1	450
CC1125 (Transceiver)	1	168
AT69170F (EEPROM)	1	72
MAAM-011229 (LNA)	1	200
TOTAL		**5878**

Table 3.3: Power budget after deployment: Uplink

3.3.3 Interfacing with PS4-OP

The system will be receiving a raw voltage of 28V from the PS4 Orbital Platform and a power of 10 Watt. D-connectors will be used to interface with the PS4-OP after which the voltage is stepped down to 3.3V to power the electrical components. ‘654Refer to figure in **Section 4.1**.

3.3.4 Power Regulation

The power received from the PS4-OP is unregulated and has fluctuations. The input received is 28V at 10W. This voltage will be brought down to the desired voltage of 3.3V and also the fluctuations will be reduced.

As seen in the figure in **Section 4.1**, First, an EMI filter(SVRMC28) is used to reduce the high-frequency fluctuations in the input power. Next a voltage regulator(SVRHF283R3S) is used to reduce the voltage from 28V to 3.3V. The circuit can be prone to unexpected increase in current and this can damage the system. Thus current limiters(TPS7H2201-SP) are used to limit the current to a maximum of 3A.

3.3.5 Power Distribution

Power received from the PS4 after being regulated by the EMI filter and the voltage regulator is used to power up the microcontroller. The regulated 3.3V is divided into 3 branches- first powers up the Comm microcontroller, second provides power to the Comm PCB and the third provides power to the ADS PCB. Refer to figure in **Section 4.1**. The power traces which act as power lines to the Communication PCB and the ADS PCB pass through a current limiter each. A separate power line is used to power the comm uC because we want the Comm uC to be ON independent of the Comm PCB to allow collection of HM data when other components on the PCB malfunction.This power line can be switched on by the elec microcontroller using a digital switch.The current limiters can be Enabled/Disabled by the microcontroller giving

HIGH/LOW voltages to the enable pins of these current limiters.

Initially when the system starts receiving power from PS4, both the current limiters are in the OFF state and hence the Communication PCB and ADS PCB are both in OFF state. The elec microcontroller(the microcontroller on AUX PCB, check figure in section 4.1) then switches on the Comm uC power line by enabling the digital switch. When a deployment telecommand is received by the system, the microcontroller turns on the ADS current limiter to start providing power to the ADS PCB and thus execute the deployment sequence.

Once antenna deployment is completed the Communication PCB will be turned on at the start of the uplink/downlink cycle. Thus, after deployment, the microcontroller disables the ADS current limiter and enables the Communication current limiter. This turns on the communication PCB.

3.3.6 Burner Circuit

This circuit is a part of the ADS PCB (refer section 7.2). The task of this circuit is to heat up a nichrome wire to cut the nylon thread which holds the two antennas. It has a voltage regulator which maintains a constant voltage across the nichrome wire. Due to the flow of current this piece of nichrome wire gets heated up and it thermally cuts the nylon wire which is wound around it thus deploying the antenna. It also has detection switches to detect the deployment.

3.4 Data Management

3.4.1 Introduction

Elec microcontroller manages data transfer between PS4-OP, ADS PCB, Comm PCB and components on AUX PCB as well. This data mainly consists of Health Monitoring Data of the system. The Health Monitoring (HM) data is the knowledge about the condition of the system to enable an assessment of its state-of-health (SoH). The SoH helps us analyse a fault in the system later or identify a potential failure during the pre-flight testing. In our system, the HM data would be stored in the EEPROM, along with a time-stamp acquired from the PS4-OP. Apart from HM data, elec microcontroller will also be responsible for sending data for telemetry and executing the telecommands as and when received. It will also interpret any uplink data, received from the comm microcontroller and execute commands if present. The Elec microcontroller will send the required HM data to Comm microcontroller which will further send through Downlink.

3.4.2 HM Data

HM data is collected from components on ADS PCB and Elec PCB and Comm microcontroller. 1 HM data string is 25 bytes long. During nominal mode, it is acquired after 1 minute and stored onboard. 36 kilobytes of data will be generated every day to be sent to PS4-OP for telemetry. Currently, 142 bits out of 25 bytes have been allocated as shown in the following table.

Data type	No. of bits	Protocol/Interface
Timestamp	32	PS4 - SPI
Uplink received or not	2	COMM - USART
Operational Mode	8	PS4 - SPI
ON/OFF comm uC, HPA, LNA	6	COMM - USART
Detection switch status X 2	4	2 GPIO pins
ON/OFF ADS PCB voltage regulator X 2	4	2 GPIO pins
Enable and Over current status - current limiter X 2	4	2 GPIO pins
DC-DC Converter Output voltage, net current drawn	16	ELEC - ADC
Temperature from thermistors : DC-DC converter	16	ELEC - ADC
Temperature from thermistors : HPA, LNA , Transceiver	24	COMM - USART
Transceiver status	24	COMM - USART
Current Sensors x 2	16	ELEC - ADC
Current Sensor x 2	16	ELEC - ADC
Total	**150**	

Table 3.4: HM Data Allocation

Pin function	Number of pins
I2C (for EEPROM)	2
SPI (for PS4-OP)	4
USART0 (pre-flight)	2
USART1 (Comm microcontroller)	2
GPIO Pins	8
ADC	6

Table 3.5: Pin Usage

3.4.3 Data Storage

HM data collected every minute during nominal mode would be stored in EEPROM. During deployment mode, rapid checking and writing of HM data will take place. Interfacing of EEPROM is done through I2C protocol. If any emergency mode is detected, the HM data taken during that time interval will also be written.

3.4.4 Interface with PS4-OP

Interfacing with PS4-OP can be done through SPI or USART, as proposed to ISRO. If SPI is chosen, then PS4-OP would be the MASTER while the elec microcontroller will be configured as SLAVE. A Harwin Connector will be used as the electrical interface. Whenever PS4-OP would give a command to send data for telemetry, all the data stored in EEPROM till that point of time will be read by the elec microcontroller and sent to PS4-OP.

3.4.5 Interface with Comm Microcontroller

Interfacing with Comm microcontroller is done through USART protocol. The elec microcontroller would be commanding the comm microcontroller to initiate the implementation of any task and also to switch its operational modes accordingly.

There will be a two-way transfer of HM data taking place in between the elec and comm microcontroller-

1. Communication microcontroller to Electrical microcontroller for storage in EEPROM
2. Electrical microcontroller to Communication microcontroller for the purpose of downlink

3.5 Flight Code and Scheduling

The Elec microcontroller has many tasks which it handles including and not limited to collection of HM data, writing the HM data in EEPROM, receiving and executing telecommand from PS4-OP and sending data for telemetry, and there needs to be proper scheduling done so that we don't have any collisions of tasks. These tasks differ according to the operational mode at that time and priority order of the tasks in that particular operational mode.

3.5.1 Operational Modes

There are 9 operations modes for our system including PREFLIGHT and LAUNCH. The in-orbit operational modes are as follows.

1. STAND-BY

   HM data is recorded from all components every minute, and stored in EEPROM, to be sent for telemetry. If and when telecommand for deployment is received, the operational mode is switched to Pre-deployment.

2. PRE DEPLOYMENT

   During this mode the ADS is powered on and the ADS PCB algorithm is executed. The HM data is recorded and stored in the EEPROM at an interval of 2 seconds, and the deployment status is checked continuously. If the deployment is successful, the operational mode is changed to post deployment.

3. POST DEPLOYMENT

   This mode is entered into when deployment is successful. Power to ADS PCB is cut off and other components on comm PCB are powered on. The initial HM data is taken from Comm microcontroller and checked. If the HM data is satisfactory, the operational mode is changed to Nominal.

4. NOMINAL

   There are two further divisions for this operational mode (wrt comm) - Nominal Uplink and Nominal Downlink. The Elec microcontroller will fall into a cycle of uplink and downlink which will start when it sends a command for the same to Comm microcontroller. During uplink mode, the Elec microcontroller will send the data to be downlinked to Comm microcontroller. During downlink mode, the Elec microcontroller will take the uplink data from Comm microcontroller.

5. EMERGENCY

   The system enters this mode when a certain component is found to be malfunctioning.

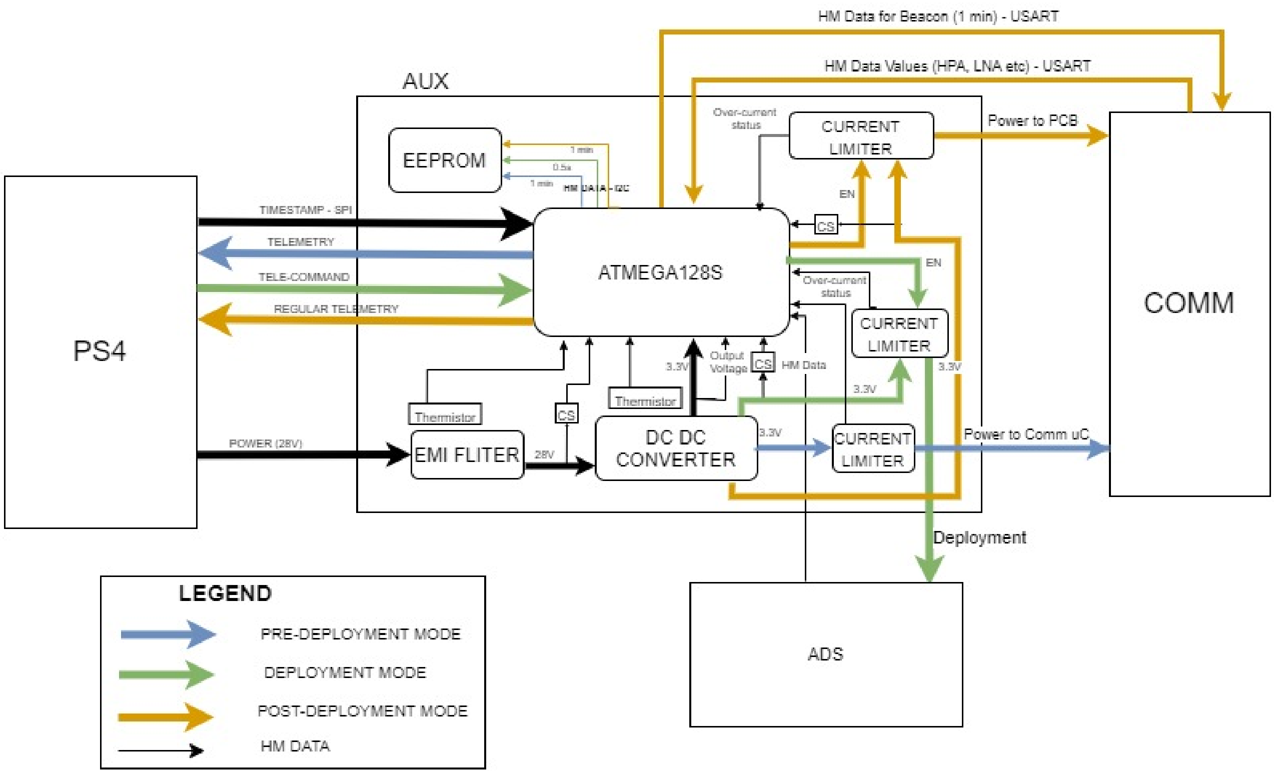
6. RESTART

   Mode in which satellite sequentially switches everything off and then switches everything on. The satellite enters this mode only when uplink/telecommand for RESET is received and verified onboard.

7. KILL

   Mode in which satellite sequentially switches everything off. After this, Power microcontroller gets itself stuck into a loop from which it cannot return. The satellite enters this mode only when uplink /telecommand for KILL is received and verified onboard.

During all in-orbit operational modes, HM data is collected at a fixed and regular interval of time (frequency of collection depends on the operational mode). Current sensors and thermistors have been placed at various positions on the PCB to record parts of Health Monitoring data. The microcontroller acquires and stores the Health Monitoring data of the system in external EEPROM between which the microcontroller also checks the ADC values constantly for any critical values. During this cycle if the PS4-OP gives us a command for Telemetry, an interrupt routine begins and the microcontroller reads the data from EEPROM and sends it through SPI.



3.5.2 Interrupt Priorities

As we have multiple interrupts in our system, we decided to have a priority order for them according to our need. But the microcontroller we are using, i.e ATmegaS128 has predefined priority order for interrupts and they can't be changed. The interrupts we are using, according to their priority levels are -

1. SPI Serial Transfer Complete

   This is the interrupt that will be used to communicate with the PS4-OP platform. Through it we will receive telecommand and timestamp and send data through telemetry. This is Highest priority as our main priority is communicating with PS4-OP.

2. USART1 Interrupt

   This interrupt will be used for communication with Comm microcontroller. Through it we will receive uplink data and HM data(Comm Board) and we will send downlink data.

3. Timer Interrupt

   This interrupt is the timer used for scheduling HM data collection and other tasks like uplink and downlink cycles.

4. USART0 Interrupts

   This is the interrupt that will be used for Pre-Flight testing.

3.5.3 HM Data Collection

We collect and store HM data every 60 seconds in every operational mode, except during PRE DEPLOYMENT, during which it is collected and stored every 2 seconds. The HM data consists of many components including ADC values, HM data from COMM PCB, Pin Statuses and the timestamp from PS4 OP.

When HM data collection begins, the timestamp from PS4 OP is taken through SPI(interrupt) and then the ADC values and Pin statuses are measured, i.e polling is done for these values. The HM data from Comm PCB is taken from Comm microcontroller through USART(interrupt) and then stored in variables.

When the HM data collection is done, the data is then immediately stored in the EEPROM. This loop is repeated every time.

3.6 Electrical PCB

3.6.1 AUX PCB

This PCB (Refer to **Figure 5.1**) performs all the major tasks to be executed by the electrical subsystem. This is responsible for power management as well as data management.

The PCB contains an EMI Filter, Voltage regulator and current limiters for the purpose of Voltage regulation/ distribution as explained in **Section 4.4** and **Section 4.5**. The next task it fulfils is interfacing with PS4-OP and the Comm PCB (refer to Comm PDR). Harwin connectors are used to act as a data and power interface between the AUX PCB and Comm PCB and circular D-connectors act as an interface between PS4-OP and the AUX PCB. It has a microcontroller which is responsible for major tasks like enabling current limiters, taking HM Data and storing it in the EEPROM, reading stored data and transferring this data to the Comm PCB/ PS4-OP for downlink/telemetry respectively, checking detection status etc. This PCB has an EEPROM to store the HM data collected by the microcontroller.

COMPONENT	SPECIFICATIONS	SELECTION CRITERIA
ATmegaS128	• 8-bit Microcontroller • 53 Programmable I/O Lines • Dual Programmable Serial USARTs • Full-duplex, Three-wire Synchronous Data Transfer via SPI • SPI offers Seven Programmable Bit Rates • ADC offers 10-bit Resolution, 8 Multiplexed Single Ended Input Channels and 7 Differential Input Channels • Voltage : 3V to 3.6V • Space grade • Operating temperature : -55°C to +125°C • Tested up to a Total Ionizing Dose of 30 krads(Si)	• Space Grade • 8 single ended ADC input • 8 external interrupts • Operating temperature : -55°C to +125°C
SVRHF283R3S (Voltage Regulator)	• Output of 3.3 V • Wide input voltage range of 18 to 40 V • Efficiency: 72% • Very low output noise • Space grade • Operating temperature : -55°C to +125°C • Guaranteed TID performance to 100 krad(Si)	• Input voltage range of 18 to 40V (works for 28V input) • 3.3V output • Efficiency 72 • Space Grade • Max current 3.3A
TPS7H2201-SP (Current Limiter)	• Input Voltage Range: 1.5 V to 7 V • Operating power consumption : 450 mW max • Ceramic package with thermal pad • Reverse Current protection • Space grade • Operating temperature : -55°C to +125°C	• Input voltage range : 1.5V to 7V • Space Grade • Adjustable Current Limit upto 6A

COMPONENT	SPECIFICATIONS	SELECTION CRITERIA
AT69170F (EEPROM)	• Voltage : 3V to 3.6V • Operating power consumption : 72 mW max • Electrically erasable and re-programmable Rad-Hard memory organized as 4Mx1bit • Space grade • Operating temperature : -55°C to +125°C	• Voltage Range: 3V to 3.6V • Space Grade • 4 Mbits On-Chip Flash Array
SVRMC28 (EMI filter)	• 28 V nominal input • 40 dB minimum attenuation at 500 kHz • Space grade • Operating temperature : -55°C to +125°C	• 28V nominal input • Space Grade • Upto 4A max current

3.6.2 ADS PCB

This PCB houses a burner circuit and impedance matching circuit. The ADS PCB is comprised of a voltage regulator, nichrome wire and detection switches to check antenna deployment. The deployment mechanism , i.e the heating of the nichrome wire only takes place when the current starts flowing through this PCB. The ADS current limiter on the AUX PCB is enabled/disabled by the microcontroller to allow current through this PCB. The voltage regulator is responsible for maintaining potential difference across the nichrome wire. A nylon wire passing over the nichrome wire will be thermally cut due to resistive heating of nichrome when current will be passed through it.. This would deploy the two coiled antennas and the deployment will be detected by two separate detection switches. This information (the detection status) will again be relayed to the AUX microcontroller to confirm deployment. 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.

Table 3.7: Components and their specifications

COMPONENT	SPECIFICATIONS	SELECTION CRITERIA
TPS-50601A-SP (Voltage Regulator)	• 1.6- to 6.3-V Input, 6-A Synchronous Buck Converter • Peak Efficiency: 95% at 3.3 V • Space grade • Operating temperature : -55°C to +125°C • Radiation Hardness Assurance (RHA) up to TID 100 krad(Si)	• 1.6 to 6.3V Input • Max current of 6A • Output voltage of 1.2 V • High efficiency: > 90
OMRON D2F-L-A (Detection Switch)	• Ultra compact basic switch with abundant terminal variation • High accuracy, high durability due to 2-spring division structure • Hinge Lever • DC Voltage rating: 30V • Operating temperature : -25°C to +65°C	• Compact and reliable • High durability

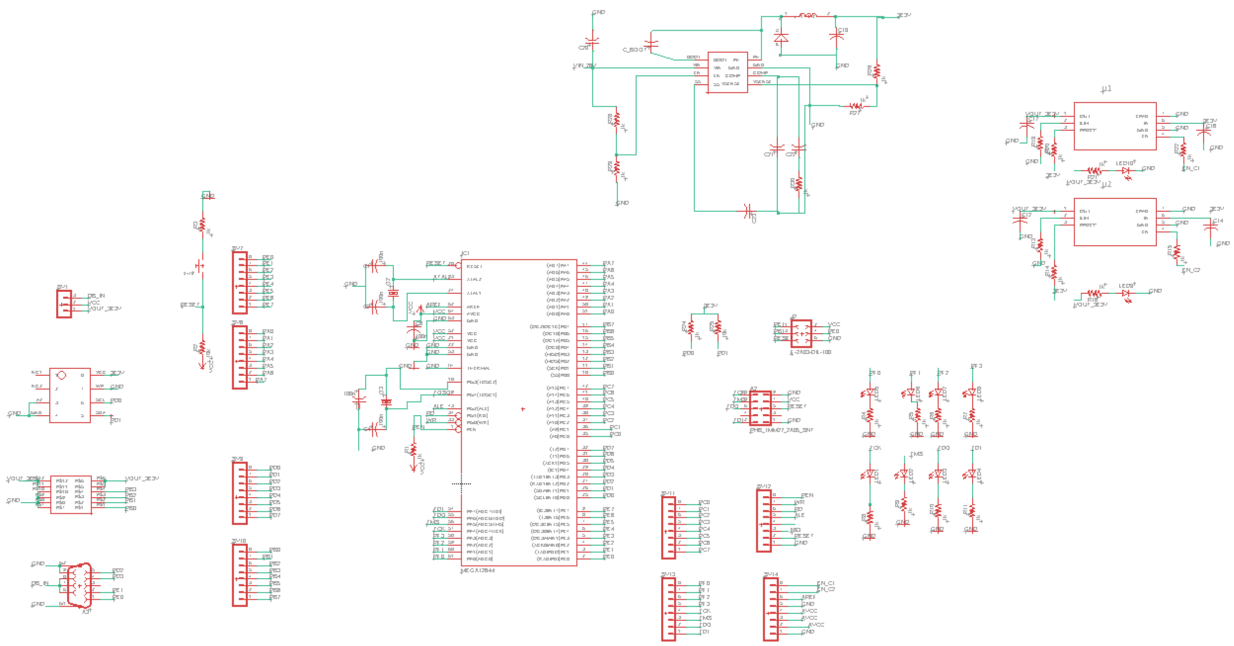
3.6.3 AUX Testing PCB

This PCB is supposed to be used for testing the circuit and also testing the flight codes. It has the commercial grade alternative of the components in the AUX PCB. So, just like the AUX PCB, this PCB also contains one microcontroller, EEPROM, Voltage regulators, connectors and regulated power of 3.3V with current limiter.

The components in the PCB include:

- ATmega128
- Current Limiter (TPS25200DRVT)
- EEPROM (AT24CM02)
- D-Connector (F09VP)
- Voltage Regulator (TPS54331EVM-232)
- Harwin Connector

Schematic of the PCB:



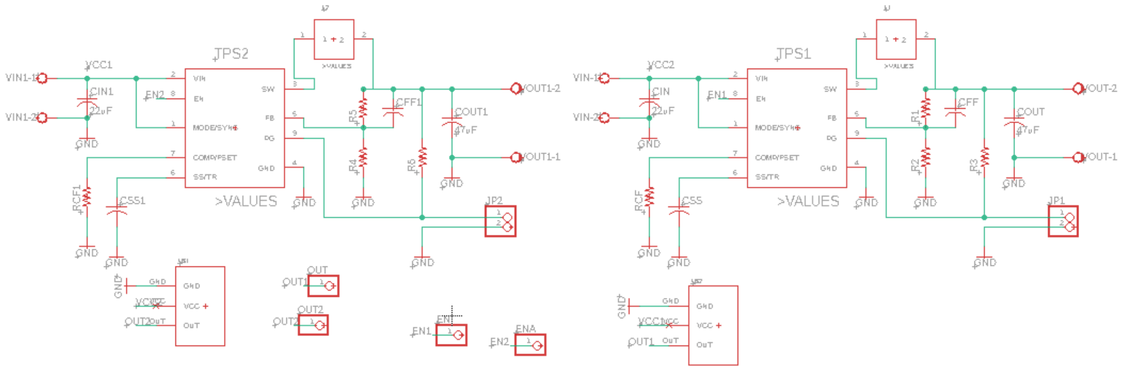
3.6.4 ADS Testing PCB

This PCB is going to be used for testing the deployment mechanism. This has commercial grade alternatives for the components used in the ADS PCB.

Components in the PCB include:

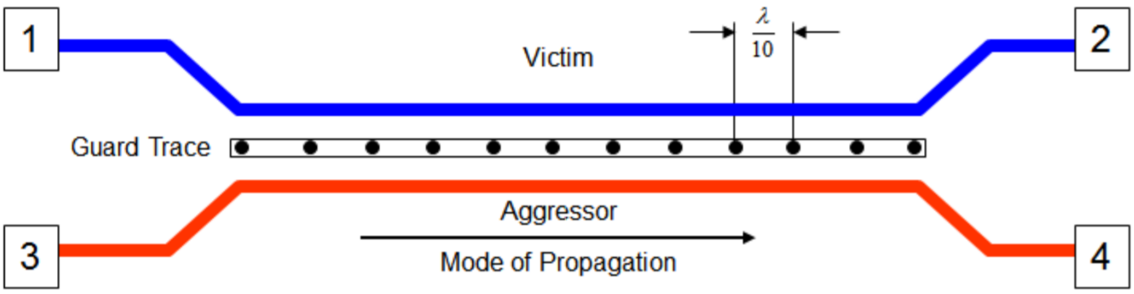
- Voltage Regulator (TPS62812)
- Detection Switch (OMRON D2F-L-A)
- Screw Connectors

Schematic of the PCB:



3.6.5 Power Isolation

Crosstalk is defined as the unintentional electromagnetic coupling between traces. In printed circuit boards, crosstalk usually occurs between two traces running side by side in the same layer or one over the top of the other in adjacent layers. This coupled energy appears as noise on the victim trace and can cause malfunctions if the amplitude is too large. A guard trace, or guard track, is a PCB trace routed co-planar between two transmission lines. Since it is a common practice, as a design rule, to specify the minimum spacing to be the same as the line width, the separation needs to be at least three times the line width in order to fit a guard trace. The guard trace should be shorted to ground, at regular intervals along its length, using stitching vias, spaced at 1/10th of a wavelength of the highest frequency component of the aggressor's signal.



3.7 Quality Assurance Practices

No matter what system we use, we will need to be sure that the objectives have been defined for the project and codes have been done correctly. Thus some guidelines are being followed to ensure utmost Quality.

3.7.1 Programming Practices

- Every time a code a written it is made modular by emphasizing more upon its logical breakdown and for easy debugging
- Modular code consists of proper comments on appropriate places, header for each function and also proper naming conventions
- Guidelines on good programming practices (including meaningful nomenclature) shared with the team members

3.7.2 Version Control and File Sharing

- Use of version control is implemented using git
- All code files regularly updated on a private repository on GitHub
- Individual persons update their GitHub repository after each change made in their code

3.7.3 Eagle Files

- A Quality Assurance Doc has been made which enlist procedures that need to be completed before ordering fabrication of PCB
    1. Filled before ordering a board by a reviewer who scrutinizes all the connection on board, both electrical and mechanical
    2. Post Fabrication PCB review - review after testing board, contains the functionality check and root cause analysis of the PCB
    3. Has the detail of each board like dimensions, handling instruc- tions and its basic functionality
- A separate folder maintained for each board containing .brd and .sch file plus a csv file and a excel file containing information about all the components used, their values and Datasheet links of ICs used in the board

3.8 Electrical Testing

Individual testing of components, to validate their features, will be done as mentioned below:

3.8.1 Current Limiter

TEST	DESCRIPTION	PASSING CRITERIA
Reverse Current Protection	V_{out} >> 3.3 V, V_{in} << 3.3 V	PG pin = High
Thermal Shutdown	$V_{in} = 5$ V	$I_{out} = 0$

Table 3.8: Current limiter

3.8.2 Voltage Regulator

TEST	DESCRIPTION	PASSING CRITERIA
Regulation	V_{in} = varying	PG pin = High
Under Voltage Lockdown	V_{in} < UVLV	PG pin = low

Table 3.9: Voltage Regulator

3.8.3 Resistors

TEST	DESCRIPTION	PASSING CRITERIA
Temperature coefficient	V_{in} = constant (varying temperature)	measured coefficient = mentioned coefficient
Power rating	$V_{in} = V_{max_{system}}$	$I_{out} \neq 0$

Table 3.10: Resistors

*

Chapter 4

Mechanical Subsystem

4.1 Introduction to Mechanical Subsystem

The mechanical subsystem is responsible for designing and manufacturing of the system structure while ensuring that the system can bear all the structural and thermal loads. This makes four major subdivisions in the mechanical subsystem.

- Structure- Ensures the structural stability of the system while launch and during the operations of the satellite.
- Thermals - Ensures that the system components are maintained in their operating temperature ranges in varied thermal cycles.
- Manufacturing - Manufactures and procures components of the system while ensuring correct dimensions and mass of components
- Integration - Integrates various components of the system to ensure the functional integrity of the system within the mass budget.

Keeping in mind the end goal of a fully functional system for the whole period of mission life, the mechanical subsystem contributes by making sure that the journey to the orbit and the harsh environment of space doesn't pose a problem to the other subsystems. The Structures division provides the basic frame of the system. Also, the antenna deployment mechanism is designed by the structures team. The Thermals team makes sure that all the components of the system are within their operational temperature throughout the mission life. The Manufacturing division checks manufacturability of the structure designed by the structure division then manufactures and procures the various components. Finally, the Integration team puts together the whole system maintaining the functional integrity of the system. They take care of the handling and transportation of both the satellite components and the fully integrated system.

4.2 Requirements

4.2.1 System Level Requirements on the Mechanical Subsystem

- The ADS module should be structurally integrable with 1U, 2U, 3U CubeSat and should be stowable and deployable.
- Mass of the system should be less than 10 kg.
- Deployment mechanism should be selected so that the antenna deploys before "X" number of attempts. Retention and deployment of dipole UHF antenna should be done appropriately.
- Antenna should be repeatedly integrable.
- ADS module should fit on the Cubesat bus without interfering with solar panels and enough space should be available to incorporate a solar panel on top of the ADS module
- Design structure for an interface compatible with ADS Module (including Screws, adhesives, joints etc.)
- Structure of the satellite should be designed to survive the launch loads prescribed in the PSLV (Polar Satellite Launch Vehicle) manual.
- Prepare a mock interface mimicking the PS4 OP interface. This interface should replicate the PS4 OP in form and functionality.
- Mechanical components should survive the space environment. They should not outgas and work in the temperature range of -40 to 85 C
- Mechanical components should qualify the environment tests
- Mechanical structure, RF interface and Burner Circuit should survive launch loads
- Mechanical structure should survive the space environment
- Provide a framework for the connectors to interface with PS4
- Design and build a transportation box for the system.
- System should have an interface to the peripheral systems(Integration fixtures, transportation box, handle) which will enable optimum integration, easier handling and safe transportation.

4.2.2 System Level Requirements on the Mechanical Subsystem

From Electrical subsystem

- Electrical components should be maintained within temperature limits
- Enough space should be allocated for the placement of components

From Communication subsystem

- Electrical components should be within operating temperature limits
- Enough space should be allocated for the placement of components
- Robust mechanical support for RF contact between antenna and traces should be provided

4.2.3 System Level Requirements from Mechanical Subsystem

From Electrical subsystem

- Size of electrical components should be compatible with mechanical design.
- Nichrome wire should not thermally damage any component.
- Size of the PCB should be 92mm x 92mm.

From Communication subsystem

- Antenna material and its dimensions should be such that it can be accommodated and effectively stowed.
- Size of electrical components and PCBs should be compatible with mechanical design.
- Size of the PCB should be 92mm x 92mm.

4.3 Structures

4.3.1 Major design decisions and developments

Antenna Deployment System (ADS)

- ADS is inspired by the commercial ADS of ISIS (Innovative Solutions In Space)

- This Figure 1. was the first configuration layout of ADS. The antennas were parallel to each other and started through the same point (SMA connector) and the electrical contact was made by tapered traces and interface blocks. The W shaped stubs were made to provide support to the top panel and keep the height of ADS fixed. The hole in the centre is for the connectors on solar panels who have height comparable to the height of ADS. It is also used to pass the wires through these connectors to the system.

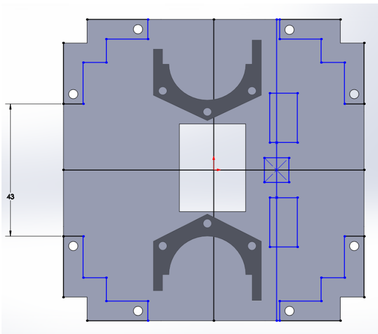


Figure 4.1: Configuration Layout

- The antennas were then shifted to opposite sides and are no longer in a single line. The C shaped subchassis are redesigned to accommodate a detection switch in it keeping in mind that the antenna is wound in an almost perfect circle. Decided to have 2 nichrome wire setups and 2 burning circuits for dual redundancy in deploying antennas.

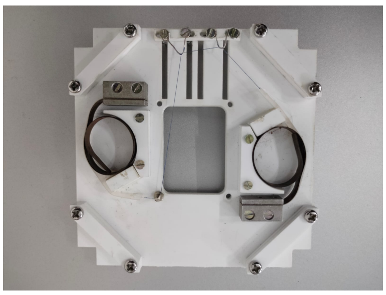


Figure 4.2: ADS Acrylic Prototype

- Now the linear stubs are proposed to be merged in pairs such that now there will be 2 bigger stubs. Each will have 6 screws, 4 for fixing the top panel to the ADS and 2 for fixing ADS to Aux.
- Eye loop hole screws are going to be used to route nylon thread in the ADS.

Sanket

- Design structure for interface compatible with ADS Module (including Screws, adhesives, joints etc.)
- The size of ADS+AUX should be 100mm x 100mm x 115.3mm (1U Cubesat standard)
- Design and build a transportation box for the ADS + AUX
- All mechanical components should survive the testing environment. They should not outgas and work in the temperature range of -40 to 85 C
- AUX should have access to the required interfaces of the testing facility
- ADS + AUX should be repeatably integrable
- Mech should provide accessories to handle the system

4.3.2 Configuration Layout

Antenna Deployment System (ADS)

Model Name: ADS_007

- The C- shaped Subchassis are used to stow the undeployed antenna in the coiled state. It is made of POM.
- A PCB acts as the base for the Antenna Deployment System. This PCB has a burner circuit and an impedance matching circuit. The dimension of the PCB is 98mm x 98mm. The thickness of the PCB is 1.6 mm.
- The detection switch is in contact with the antenna when it is in a coiled state. It is therefore used to detect if the antenna has deployed or not.
- The dipole antenna 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 modelled in HFSS software for minimum S11 (input port voltage reflection coefficient) in the required frequency band.

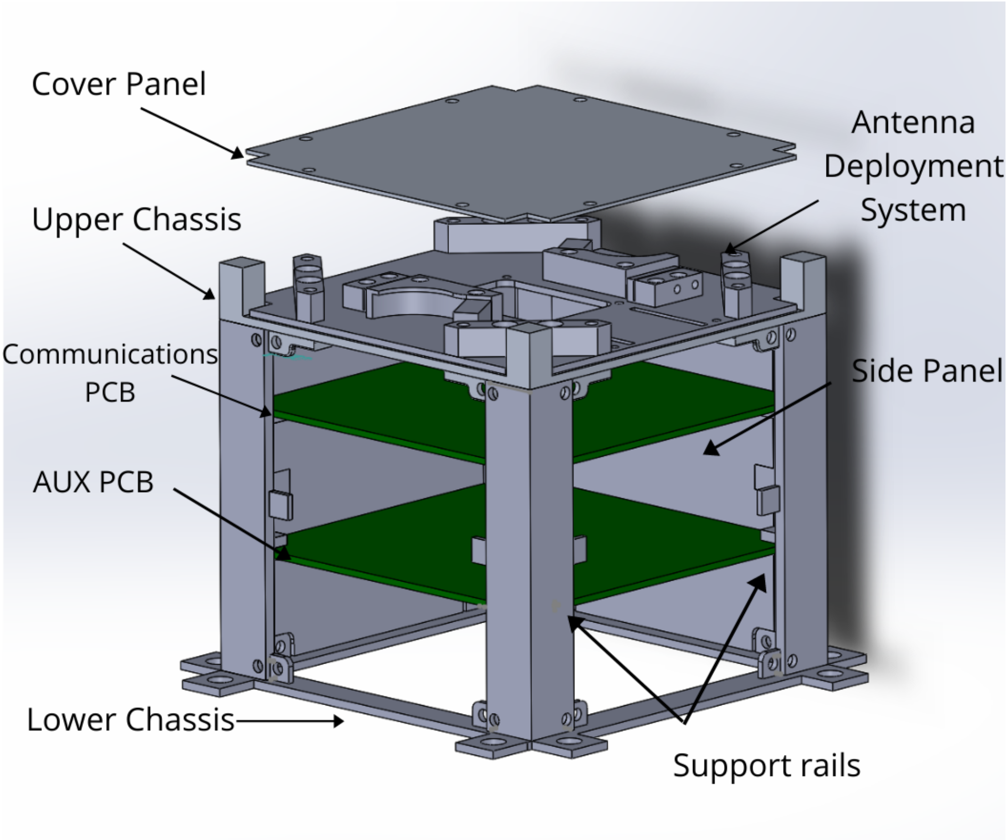


Figure 4.3: Sanket Rendered CAD Model

- Interface block acts as the interface between antenna and the tapered traces on the ADS PCB. PVC sheet is also fixed along with the antenna and the interface block to hold the antenna in its coiled position. The PVC sheet in turn is attached to the nylon wire.
- Nichrome wire is used as a heating element in the burn-wire circuitry. A 1.5 cm long, 32 AWG nichrome wire is used.
- Nylon wire is used as the burning element. It passes through the nichrome wire, and it melts when current is passed through the burn-wire circuit, causing the antenna to deploy.
- The PCB is attached to the linear stubs through the two holes in the middle. The other two holes are used to join the ADS module to the Auxiliary system.

Sanket

- The entire system is attached to PS4-OP through the lower chassis with the help of 8 M6 screws.
- The support rails are attached to the lower and upper chassis and the electrical and communication PCB are screwed on the horizontal stubs in the support rails.

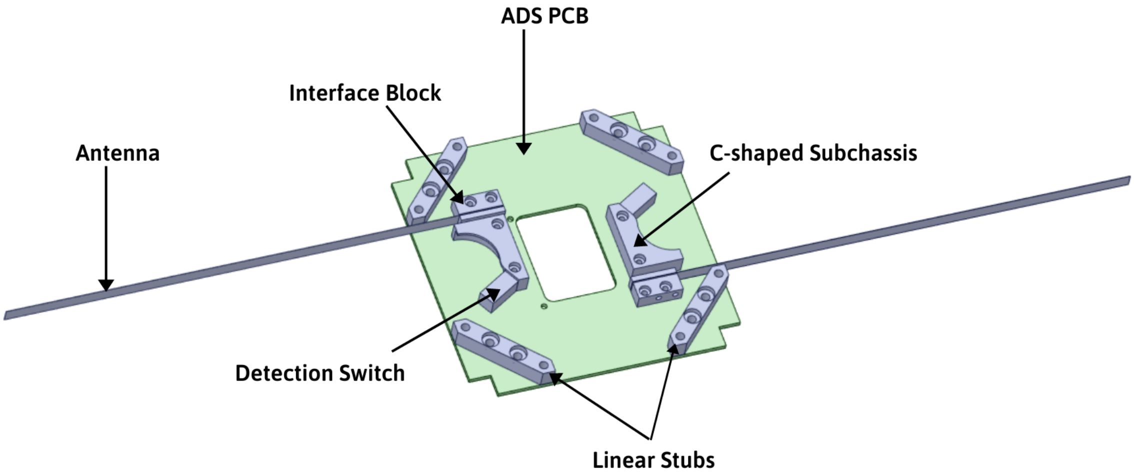


Figure 4.4: ADS CAD Model

- The electrical PCB is placed below the lower set of horizontal stubs and the communication PCB is placed above the upper set of horizontal stubs as the electrical PCB cannot pass through the upper set of the horizontal stubs and be placed above the lower set of horizontal stubs
- The side panels are attached to the upper and lower chassis.
- The electrical interface with the ps4op is through a connector present on the electrical PCB and goes through a hole is present in the side panel.
- The ADS PCB sits on the upper chassis and is connected to the auxiliary system via screws.

4.3.3 Mass Budget

ADS		
Serial number	Component(s)	Mass(g)
1	Voltage Regulator	1.22
2	Cover Panel	25.17
3	Antenna	8.64
4	ADS PCB	26
5	C Subchassis	3.3
6	Interface block	4.48
7	Linear Stubs	5.26 X 4
8	Detection Switch	10
9	Inductor	0.22
	Total	100.07
	Integration(10%)	10
	Total (ADS)	110.07

Table 4.1: ADS Mass Budget

Sanket		
Serial number	Component(s)	Mass(g)
1	ADS	110.07
2	Elec FR4 PCB	20.36
3	Comm FR4 PCB	20.36
4	Comm microcontroller	4.8
5	M6 Connector(40 mm)	12.3 X 8
6	Voltage Regulator	27
7	Current limiter	3.12
8	EMI Filter	52
9	Elec microcontroller	4.8
10	EEPROM	1
11	Top Cage	27.31
12	Bottom Cage	20.23
13	Support Rails	17.42 X 4
14	Side Panels	47.23 X 4
	Total	648.05
	Integration(10%)	65
Total(Sanket)		713.05

Table 4.2: Sanket Mass Budget

Mass Budget (Total Mass - 713.05 g)

4.3.4 Material Selection

Component(s)	Material
Top and Bottom Cages	Al 6061-T6 (SS)
Support Rail	Al 6061-T6 (SS)
Side Panel	Al 6061-T6 (SS)
Cover Panel	Al 6061-T6 (SS)
Antenna	Tape Spring(Stainless Steel)
ADS PCB	FR04
C Subchassis	POM
Interface Block	Al 6061-T6 (SS)
Linear Stub	Al 6061-T6 (SS)
Retaining Element	PVA/PVC
Nylon Thread	Nylon
Nichrome Wire	Nichrome

Table 4.3: Material Properties

Properties	Al 6061	FR04	Copper
Density(g/cc)	2.7	1.85	8.92
Young's Modulus (GPa)	68.9	22	117
Yield Strength (MPa)	240	68	70

Table 4.4: Material Properties

- Al 6061-T6 (Structure of Cubesat) - It was chosen due to its space heritage. This material has the best balance of strength to weight ratio, manufacturability and availability.
- C shaped subchassis - Insulating material was required as the antenna may oscillate and touch the chassis after deployment, which will change our radiation pattern. Polymers were the best option, among which POM(polyoxymethylene)trumped considering its space heritage and outgassing properties.
- Antenna - We tried BeCu(beryllium copper) alloy due to its shape retaining property but rejected due to too much bend in it. Tape springs(made of stainless steel) have been used in various missions - it is a good conductor as well as retains its shape.
- Nylon Thread - Dyneema was used in various missions, but it was found to be difficult to procure. Nylon is used as well, but it is not that strong so we used a braided thread. It exhibits less outgassing and can sustain launch loads as well. Actively searching for other better alternatives such as Vectran.
- Linear Stubs - Al 6061and POM could both be used for this. These components needed strength as they are the supporting structure for the complete ADS, which Al 6061 provides. Threading was also required in the stubs for screwing things together and

threading is not possible in thin sections or reliable either, in polymers, so Al 6061 was chosen.

- PVA/PVC - A flexible material for keeping antenna in undeployed configuration was required. Low outgassing and space heritage material like PVC proved useful.

4.3.5 Loading

The satellite is carried to orbit(currently LEO) by a launch vehicle in a flight of about 17 minutes. During this period, the vehicle experiences a high degree of acceleration, vibration and shock, transmitted to the payloads attached to its flight deck. Launch loads which are experienced include static, vibrational, acoustic and shocks and impose strict requirements on the structure of the satellite. The structure should be able to withstand these loads during launch. All the components ought to be safe and in working condition after launch. The loading specification of the Sanket system is taken to be the same as for a satellite during launch.

Static Loading

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

Table 4.5: 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 4.6: Harmonic Vibration Loads

Random Loading

	Qualification	**Acceptance**
Frequency (Hz)	**PSD** (g2/Hz)	**PSD** (g2/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 4.7: Random Vibration Loads

4.3.6 Modelling & Simulations

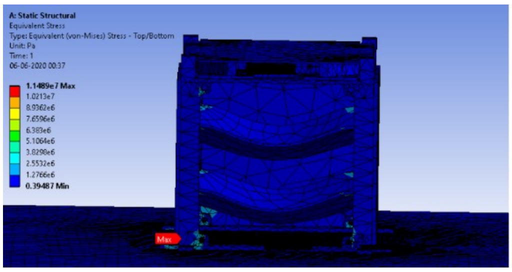
Software - Ansys was used for structural simulation of satellite Model Name - SAT0010017

- Boundary condition:
  The lower chassis fixes the satellite system on ps4op with the help of screws and is simulated for launch loads of pslv.
- Modelling of material properties:
  Electrical, Communication and ADS PCBs and the side panels are modelled as plates (midsurfaced) by the help of shell modelling.They are modelled as uniform distributed mass. Antenna is not modelled explicitly in simulation but its mass is accounted in the PCB of ADS. The material used for the subchasis is POM , PCBs is FR4 and the rest of the auxiliary and ADS system AL6061.
- Joints:
  Fixed joints have been used to model screws. Concentric surfaces were interfaced with the joint to simulate the bond a. Fixed joints - All degrees of freedom are constrained.
- Contacts:
  Bonded contacts were modelled to simulate adhesives used between two surfaces and are defined between a few of the ads pcb components.
- Meshing:
  Standard auto meshing was used in models Maximum elements were of the tetrahedron class, meshed at the structure and other intricate places. Shell modelling was used for the pcbs and side panels.

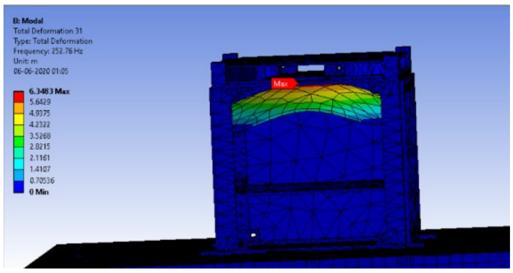
4.3.7 Simulation Results

Simulation Result Analysis: In order to investigate the structural safety of Sanket under 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 simulation results (ref. Table 1). We try to achieve FOS>1.5.

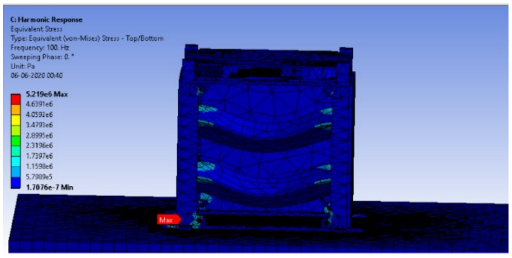
$$Factor\ of\ safety = \frac{Yield\ Stress}{E} \tag{4.1}$$



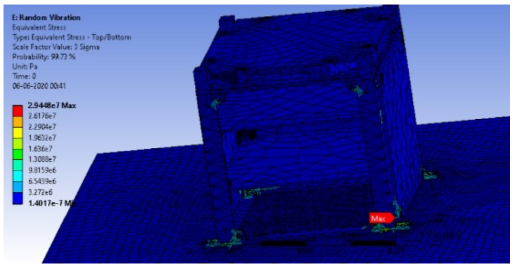
(a) Static Stress Analysis



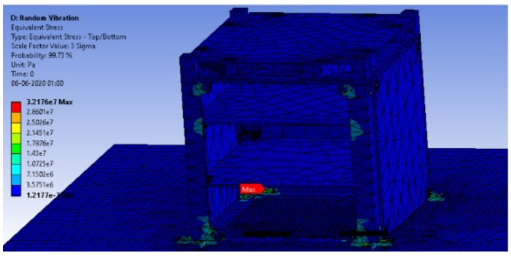
(b) Modal Analysis- 1st Mode



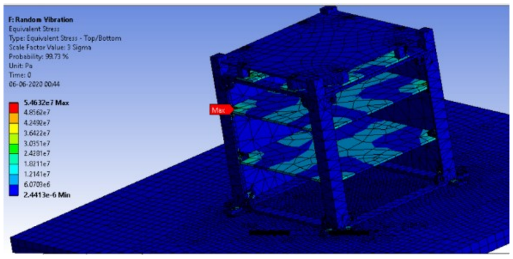
(c) Harmonic Response Analysis



(d) Random Vibration Analysis (x-axis)



(e) Random Vibration Analysis (y-axis)



(f) Random Vibration Analysis (z-axis)

	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
Safety Factor	23.93	-	52.68	9.34	8.55	2.20

Table 4.8: Results of Structural Simulation

4.3.8 Radiation Shielding

1. Introduction

   A traditional, rigorous radiation analysis and mitigation method could increase the cost and time of the development of CubeSat missions and hence might not fit the principle of small satellite missions. Thus, a simple and low-cost framework for radiation analysis and mitigation for Low Earth Orbit (LEO) small satellites was used, as outlined in several sources. Even though it is well understood that the radiation environment in LEO is more benign than higher altitude orbits, there is still a considerable amount of radiation that can fail LEO satellite missions. Moreover, the South Atlantic Anomaly (SAA) penetrates deeper into the Earth's atmosphere. This poses a particular hazard to Near-Equatorial LEO satellites crossing the region frequently. With the used framework, it is possible to quickly analyze the expected radiation doses and effects and implement suitable mitigation techniques.

2. Radiation Environment in LEO

   Radiation is the emission or transmission of energy in the form of waves or particles through space or material medium. As radiation interacts with matter, it loses energy. The energy loss corresponds to the damage to electronic components due to radiation and can be categorized as ionising damage and non-ionising damage :

   - Ionising damage is a radiation damage in semiconductor materials caused by the excitation of electron-hole pairs, i.e. generation of charge
   - Non-ionising damage refers to lattice damage to material through collisions. Any damage in material and tissue or electronic components due to atomic displacements is non-ionising damage.

Ionising damage can be further classified into two types :

- Total Ionising Dose (TID) is a measure of the cumulative ionising radiation received by a material over a period. Such radiation causes permanent degradation in electronic components due to cumulative ionizing radiation over the time span of the satellite mission.
  It is usually measured in krad = 1000 rad = 10 Gray = 10 J/kg.
- Single Event Effects (SEE) is a disruption in the function of electronic circuits caused by penetration of a single highly energetic heavy ion deep into a device.

Non-ionising damage is quantified by Total Non-Ionising Dose(TNID). Surface or bulk material charging is also another, relatively benign concern.

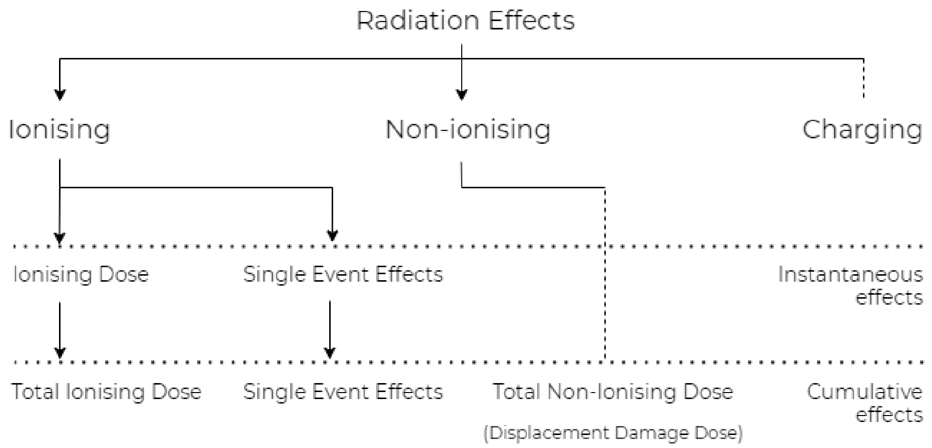


Figure 4.6: Types of radiation effects

Radiation Environment is dynamic, it can be said to comprise of two zones :

- Outer zone: very dynamic and composed of predominantly electrons, experiences solar particle events and galactic cosmic rays. It impacts Medium Earth Orbit(MEO), Geostationary Earth Orbit(GEO) and some polar orbits.
- Inner zone: composed of electrons and protons, relatively stable for LEO and high LEO. Most common LEO orbits are inside the inner zone and exposure is limited to auroral and South Atlantic Anomaly(SAA) passes.

Sources of radiation in space can be grouped into two main categories :

Natural Space Environments

- Galactic Cosmic Rays(GCR) are protons, alpha particles, and heavy ions majorly originating outside the solar system.

  Relatively constant effect, varies slowly with time - times two flux modulation with the solar cycle(maximum during solar minimum).

  Threat: SEE, TID/TNID for astronauts

- Solar Wind

  Always present in the background, density and velocity vary with the presence of coronal holes(which vary with the solar cycle - maximum during declining phase and solar rotation).

  Threat: Surface charging, TID for surface materials
- Solar Particle Events involve solar energetic particles, which are electrons, protons, alpha particles and heavier charged particles emitted by the sun during solar flares and coronal mass ejections.

  Probabilistic in nature - its time and direction vary with the solar cycle. It is dependent on solar radiation and solar magnetic field.

  Threat: TID, TNID, SEE
- Trapped Particles are protons and electrons trapped inside the Earth's geomagnetic field.

  Relatively constant inner belt, outer belt is dynamic, slot region very dynamic, there are transient belts.

  Varies with solar cycle - maximum during solar minimum.

  Threat: TID, TNID, SEE(inner belt), internal charging(outer belt, slot region)
- Radioactivity
- Ultraviolet radiation

Man-made Environments

- Nuclear Weapons
- Radioisotope Thermoelectric Generator

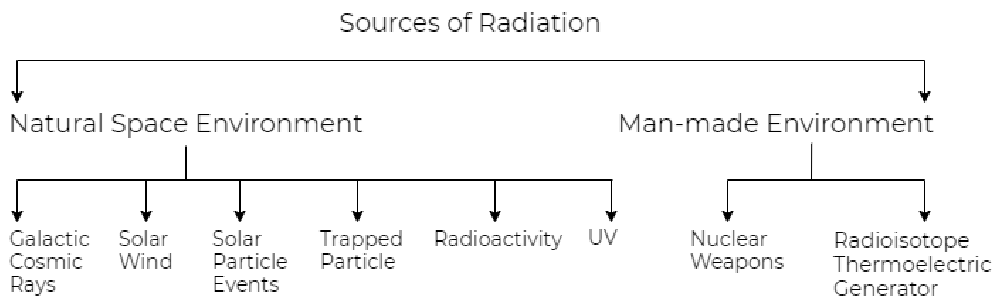


Figure 4.7: Types of radiation effects

There are mainly three sources of radiation in LEO: trapped particles, solar energetic particles, and galactic cosmic rays. Contributions from these three sources to radiation damages vary according to the compositions and the level of energy.

Radiation Source	Particle Type	Effect on Electronics
Trapped Particles	Electrons	TID
	Protons	TID, SEE
Solar Energetic Particles	Electrons	TID
	Protons	TID, SEE
	Heavy Charged Particles	SEE
Galactic Cosmic Rays	Protons	TID, SEE
	Heavy Ions	SEE

Table 4.9: Sources of radiation in LEO and corresponding effects

Even as non-ionising damage exists, radiation effects on electronic devices in space majorly come from ionisation and as such, primarily they are the ones simulated to address concerns in radiation shielding.

3. Modelling of Simulations

   In order to calculate the expected radiation dose, the radiation environment model, satellite model, and the orbital parameters to be used in the simulations must be defined. Simulations are performed in the Space Environment Information System (SPENVIS), a free web-based software provided by ESA that includes many industry-standard space radiation effects analysis tools. These tools allow numerical simulation of radiation effects. Shielding thickness of satellite panels' influence on radiation effects can be analyzed.

   (a) Radiation Environment Model
   While defining the radiation environment, the following factors must be kept in mind :

   - Temporal and spatial variations, including
     - 11-year solar cycle
     - 21-day solar rotation
     - Sun or shadow(eclipsed situation)
     - Earth's magnetic field
   - Key parameters, like
     - Launch date
     - Mission duration
     - Orbit parameters
     - Confidence level for some models

   For TID for electronics and shielded materials(which is the case here)

   - Need to incorporate trapped particles and solar particles
   - Can ignore GCR contribution
   - Use AP9/AE9/IRENE(with appropriate confidence levels) or AP8/AE8(with appropriate design margins) and ESP/PSYCHIC(with appropriate number of active years and confidence levels)

AP9 and AP8 are numerical models of trapped protons, AE9 and AE8 are numerical models of trapped electrons and ESP and PSYCHIC that of solar particle fluences.
The International Radiation Environment Near Earth (IRENE) radiation belt and space plasma specification model software suite provides estimates of trapped energetic electrons, energetic protons, and plasma from the AE9, AP9 and SPM models, for use in space system design, mission planning, and other applications of climatological specification.

For SEE environments, need to

- Use CRÈME model suite on Spenvis for heavy ions
  Cosmic Ray Effects on MicroElectronics (CRÈME) model suite was developed by the Naval Research Laboratory (NRL) to assess the SEU rates in the radiation environments that can be expected during space missions.
- Protons from the same environment used for TID

Among the three primary sources of radiation, for trapped particles, we make use of the AP-8 and AE-8 trapped radiation environment models developed by NASA's National Space Science Data Center (NSSDC). They are used here because the AP9 and AE-9 are currently provided for evaluation purposes only in Spenvis, and because uncertainties are still inevitable anyway. While, even though AP-8 and AE-8 have been the standard for trapped particle models for decades, they bear an uncertainty of "about a factor of 2" according to their author.
For solar energetic particles, the JPL fluence model developed by the Jet Propulsion Laboratory (JPL) is used. The ISO-15390 space environment (natural and artificial) will be used for galactic cosmic ray model developed by the International Organization for Standardization (ISO) Technical Committee ISO/TC 20, Aircraft and space vehicles, Subcommittee SC 14, Space systems and operations.
An interesting observation while handling these models is however, that solar maximum is the best case for radiation shielding purposes and solar minimum is the worst case, as those terms reflect atmospheric effects.
Note: While using Spenvis, it is a good practice to use the PNG file format for plotting graphs as the graphs generated occupy the limited storage space each user has on Spenvis, to preclude the possible need for removing results with the limit being reached.

(b) Satellite 3D Model

The inclusion of the satellite model in the radiation analysis is allowed by the use of the Sector Shielding Analysis Tool (SSAT) based on GEANT4 contained in SPENVIS. For this simulation, the conversion of CAD into STEP and GDML file formats(from STEP, using software like Fastrad) was foregone. The Geometry Definition tool - part of GEANT4 tools - within Spenvis was used to define the satellite model in GDML. There is also a provision for VRML visualisation of the geometry defined, like the image at the end of this section.
GDML or Geometry Description Markup Language is a numerical model file format

used to describe geometries for physical simulations and analysis applications. For the purpose of this simulation, a relatively simplified model was used to reduce computational time(as computational time available to each user on Spenvis is restricted by design). The results from the simulation are however, still valid, given the level of uncertainty and randomness in the charged particle spectra and the accuracy of the radiation environment models. Sanket is a 1 U CubeSat, with the ADS sitting on the top face. This was modelled as a 10 cm × 10 cm × 10 cm hollow box of uniform thickness 3 mm.

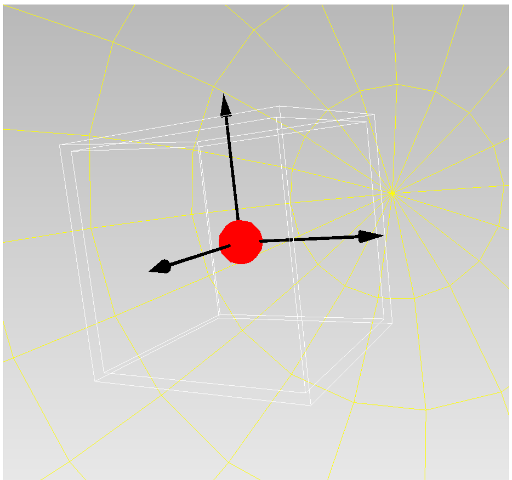


Figure 4.8: VRML visualisation of GDML definition of Sanket

(c) Orbital Parameters

Orbital parameters are crucial as different orbit trajectories experience different radiation environments. For the current simulation, Pratham's(IIT Bombay's first student Satellite) TLE to define the orbit. The orbital parameters(Keplerian elements) obtained from Pratham's TLE at one-month intervals were used, for a total mission duration of 4 months - the prospective mission length of PS4-OP.

	Plasma (charging)	Trapped protons	Trapped Electrons	Solar Particles	Cosmic Rays
LEO(low inclination)	No	Yes	Moderate	No	No
LEO(polar)	No	Yes	Moderate	Yes	Minimal
GEO	Yes	No	Severe	Yes	Yes

Table 4.10: Summary of Radiation Environmental Hazards

4. Simulation Results and Mitigation

Simulations are performed to analyze TID and SEE. The first step of the simulation is to find out the radiation environment specific to PS4 OP's presumed orbit. Simulations based on all three radiation environment models mentioned earlier are performed to find out the contribution from each of these sources. From our simulation, it is evident that solar energetic particles do contribute to radiation along our orbit, while the flux of galactic cosmic rays (from Hydrogen to Uranium ions) is too low to contribute to the cumulative radiation experienced even as their energy can be orders of magnitude higher than the trapped particles. Earth's magnetic field functions as a shield to prevent galactic cosmic rays from significantly penetrating LEO, even in the polar region.

Radiation Source	Energy (MeV)	Flux (particles/cm^2)(Integral)
Trapped Protons	0.1 - 400	3.56×10^{10} - 1.81×10^{7}
Trapped Electrons	0.04 - 6	4.32×10^{13} - 2.18×10^{7}
Solar Energetic Particles	0.1 - 500	8.44×10^{10} - 4.15×10^{6}
Galactic Cosmic Rays(H)	1 - 10^5	6.83×10^{2} - 3.45×10^{-1}

Table 4.11: Summary of Radiation Environmental Hazards

(a) Total Ionising Dose

TID effects in electronics originate from parametric degradation leading to functional failure. Effects include threshold voltage shifts, reduced gain, leakage(increases power consumption), timing changes and decrease in functionality.

Based on the radiation environment specific to the defined orbit - calculated from the models for the three different sources of radiation, the received cumulative ionising dose over the mission period can be estimated. Spenvis's SHIELDOSE-2 determines the absorbed dose as a function of depth in the aluminium shielding, expressed in a graph called the dose-depth curve.

The dose depth curve for TID integrates the various particle spectra(from the models) against a damage function(from the detector used, Silicon in this case). It is very useful but limitations include loss of species information, energy information(as it integrates all doses of a similar type for simplicity) and limitations in the damage function. This curve specifies the expected TID only for isotropic simple geometry in shielding, such as an aluminum solid sphere(which is used in our simulation).

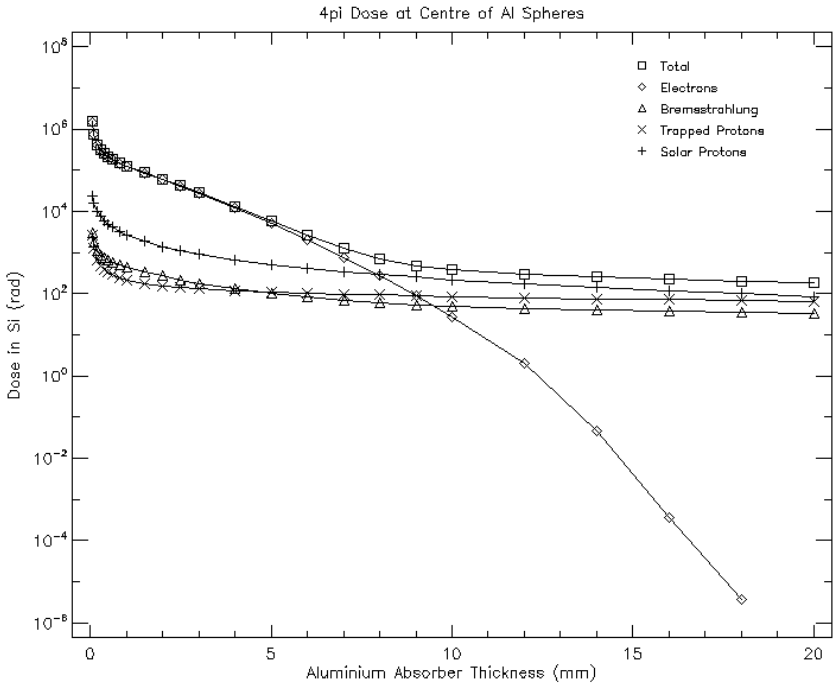


Figure 4.9: Dose-depth curve for Sanket

From the dose-depth curve obtained from the simulation, it can be seen that solar protons contribute the most to the total dose. The shielding equivalent to 1 mm of aluminium can lower the total dose by one order of magnitude. More than 5 mm of aluminium does not give any further significant shielding effect, but 18 mm of aluminium can completely block electrons. It can be seen as well that the maximum TID over the mission is around 1000 krad with zero shielding, which shows that TID is a grave concern.

In order to calculate TID in anisotropic shielding as can be found in real spacecraft, we use the Small Sector Analysis Tool(SSAT). SSAT determines the shielding distribution of a spacecraft using the ray-tracing method at a user-defined point within the geometry. It divides the shielding structure into small angular sectors, called direction windows, in terms of polar angle θ and azimuthal angle ϕ, with respect to all 4π solid angles. The figure below illustrates the concept of direction window as implemented in SSAT. At the origin of the polar/azimuthal angles is a fictitious geantino particle, which undergoes no physical interactions, but however flags boundary crossings along its rectilinear trajectory. Using knowledge of the positions of these boundary crossings, in consonance with the density of the material used in shielding can be used to profile the shielding for a given point within the spacecraft. The TID at the location of the geantino particle(detector, as defined in Geometry definition) can be calculated by summing all the ionizing dose values that have penetrated through every shielding sector, i.e. the direction window. This can be written in an equation as follows

$$\mathbf{TID} = \sum_i \frac{F_i(t)d\Omega_i}{4\pi} \tag{4.2}$$

where $F_i(t)$ is the absorbed dose for a given thickness t (taken from the dose-depth curve), $d\Omega_i$ is the differential solid angle of the shielding sector, and i is the index associated with each sector.

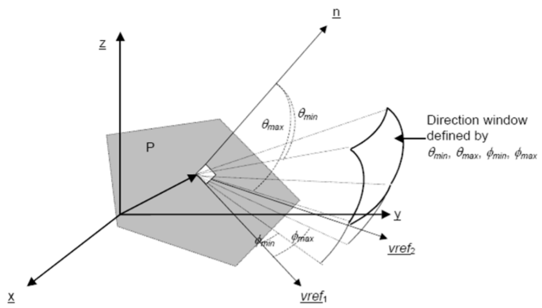


Figure 4.10: SSAT's direction window for calculation of shielding distribution

For this simulation, a binning system corresponding to the default binning system in SHIELDOSE-2 was defined and the dose-depth curve data obtained earlier uploaded in the requisite format. The spacecraft was divided into 648 shielding sectors - 18 polar bins and 36 azimuthal bins. The calculation point is located at the geometric centre and visualisation of the ray-tracing is also opted for. There is a limit to how much the shielding can block radiation and we need to balance radiation damage concerns with those arising from inflation of mass budget or lowering of internal volume. While the simulation does illustrate that aluminium shielding is an effective mitigation technique for TID.

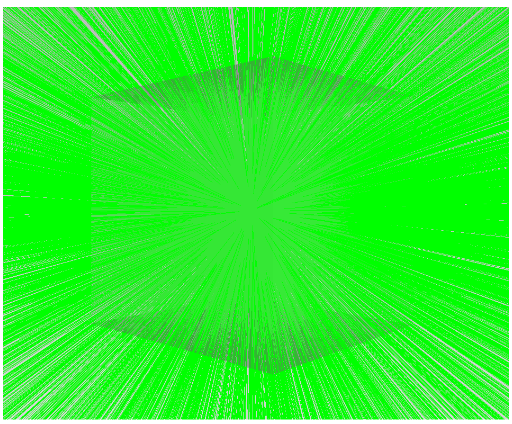


Figure 4.11: Ray-tracing from detector in the model of Sanket

Given below is an overview of the methodology followed for simulation and mitigation of TID for small satellites.

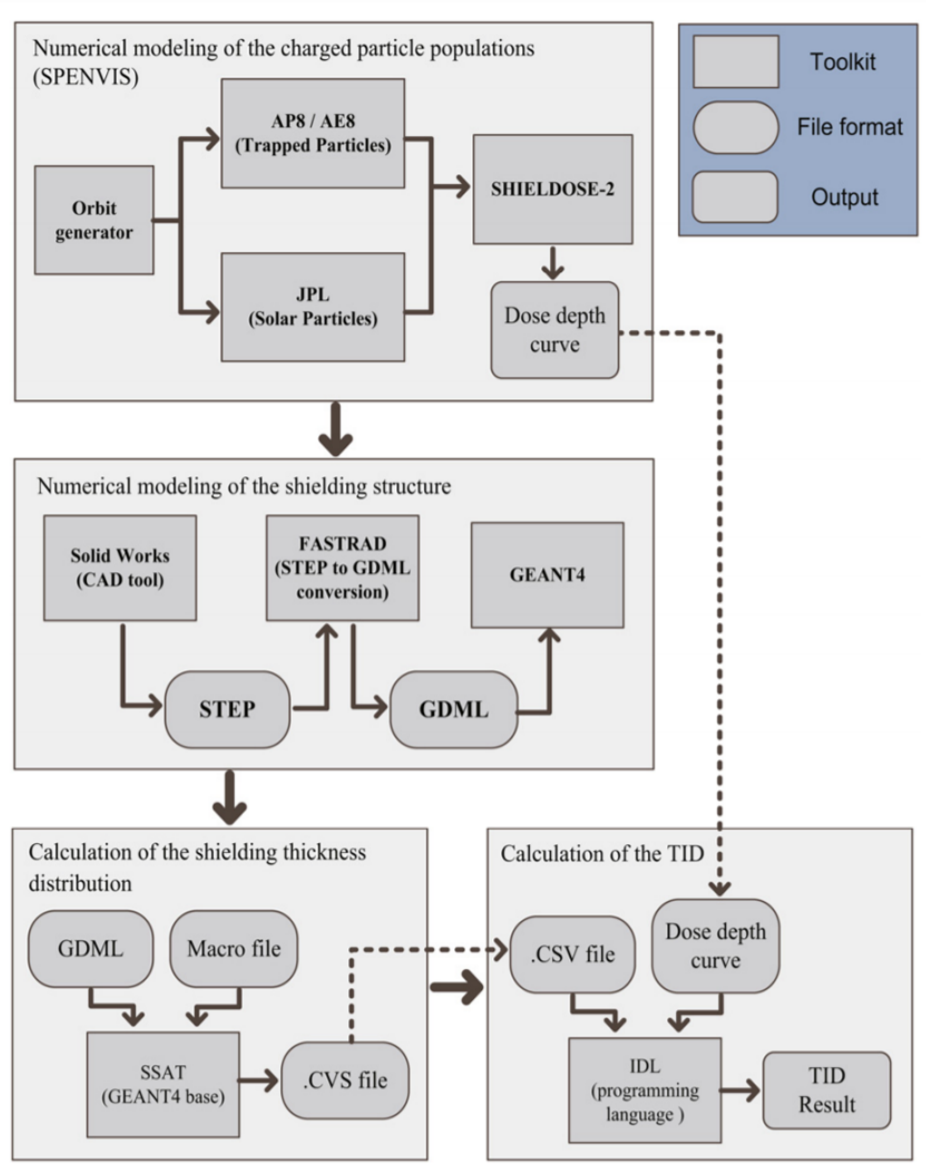


Figure 4.12: Block diagram of procedures implemented to perform total ionising dose calculations

The relative relationships between the toolkits and the sequence of calculations are presented in the following order :

i. numerical modeling of charged particle populations
ii. geometrical modeling of the shielding structure
iii. calculation of shielding thickness distribution
iv. calculation of TID.

In the above figure, different shapes are used to represent the toolkits, file formats and outputs. Arrows and dashed arrows indicate the sequence, logical flow, and input for each toolkit.

(b) Single Event Effects

Single Event Effects (SEE) happen randomly by nature and hence are more difficult to predict. SEE can be

- Destructive effects, where the part is incapacitated or shorted
  i. Single Event Latch-up(SEL) are short circuits caused by a single energetic particle; may cause permanent damage if not mitigated
  ii. Single Event Burnout(SEB) are most common in power MOSFETs
  iii. Single Event Gate Rupture(SEGR) are also most common in power MOSFETs
  iv. Single Event Dielectric Rupture(SEDR)
- Non-destructive effects
  i. Single Event Latch-up(SEL)
  ii. Single Event Upset(SEU) are changes in the state of memory elements
     Single bit upset(SBU)
     Multi bit upset(MBU)
  iii. Single Event Transient(SET)
  iv. Single Event Functional Interrupt(SEFI)
  v. Stuck bits, or persistent SEU

SEE effects can be quantitatively examined using a quantity called Linear Energy Transfer (LET), which describes how much energy an ionizing particle deposits into a matter per unit distance. A simulation run on SPENVIS's CRÈME software can show the flux spectra as a function of LET values on Silicon material, for the orbit defined. The sensitivity of a component to an SEL can range from LET values from 1,000 MeV cm^2 g^{-1} to above 50,000 MeV cm^2 g^{-1}.

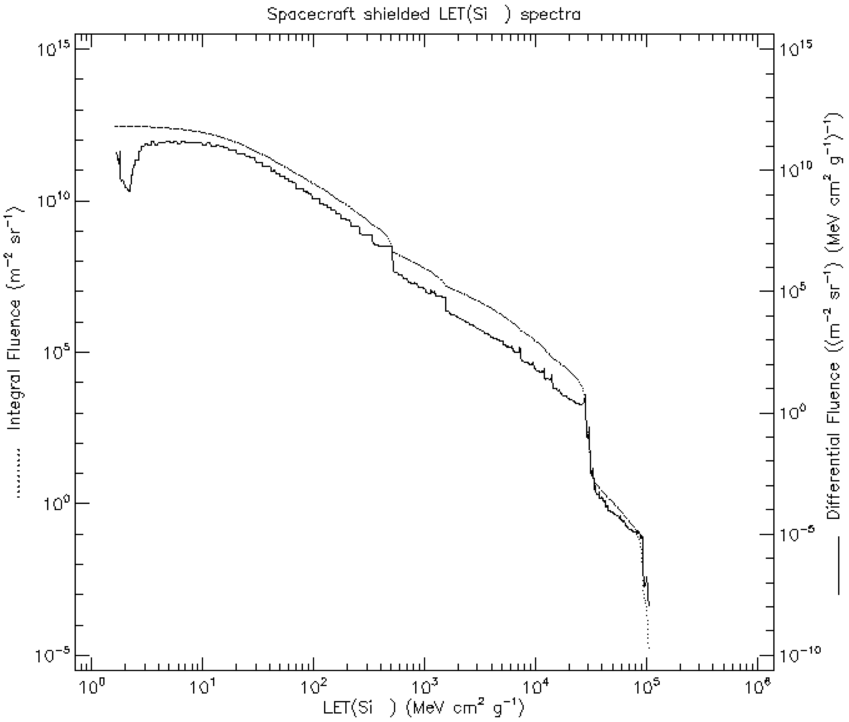


Figure 4.13: LET spectra along defined orbit

In the simulation for Sanket, flux for particles providing LET of 1,000 MeV cm^2 g^{-1} is about 10^7 particles m^{-2} sr^{-1} while for 50,000 MeV cm^2 g^{-1}, the flux is less than 1 particle m^{-2} sr^{-1}. This demonstrates that Sanket is subjected to SEL and possibly other kinds of SEE. Due to their damaging nature, SEE have to be taken into consideration.

Mitigation techniques called the Fault Detection, Isolation and Recovery (FDIR) have to be implemented on-board the satellite during the design phase. FDIR policy is commonly categorised into two levels

- Low-level FDIR: primarily tasked with protecting system from SEL and to restart parts that fail in an unrecoverable way due to other SEE
- High-level FDIR: tasked with mitigating errors that occur due to SEE without affecting the operation of the satellite.

(c) Conclusion and Design Changes

The main structures for Sanket are made of aluminium. The 3 mm aluminium panels are designed for high mechanical stiffness, good radiation shielding, good thermal stabilization and good electrical grounding. The antenna PCBs also provide some radiation shielding. These PCBs are typically composed of multiple layers of coppers on an FR04. Therefore, the components on ADS PCB are on the bottom side for protection from radiation.

Thus a simple yet fairly comprehensive framework for radiation analysis was implemented. Using this framework, it was assessed that Sanket would survive the radiation environment for the mission duration with the proposed changes. With respect to the shielding as analysed through SSAT, the maximum TID for Sanket is estimated to be 13 krad over 4 months. As our initial goal was to limit TID to 10 krad and we obtained TID of 5 krad over the mission period for 3.5 mm shielding of the same material - which was deemed overkill - it was decided to go ahead with ensuring 3 mm(Al) shielding for the entire satellite, wherever feasible. It was also assessed that Sanket shall experience SEE. Owing to the values found in the LET spectra, basic, low-cost and yet robust FDIR techniques are required to help the satellite survive SEE.

5. Future refinements

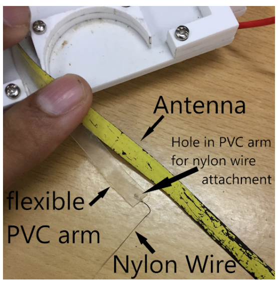
   The immediate plan is to run simulations again for the range of values of inclination pertaining to sun-synchronous Low Earth Orbits - the type of orbit it is assumed, PS4-OP shall continue to stick to for future missions.
   While, the past two missions of ISRO labelled PS4-OP, on January 24, 2019(PSLV-C44) and on April 1, 2019(PSLV-C45/EMISAT Mission) had inclinations of 98.767±0.2° and 97.468° respectively.

   In the simulation, aluminium was taken as the material, instead of the Al-6061 T6 alloy that shall be used on the satellite - which can have up to 98.56% aluminium. Defining a material closer to the actual alloy for future iterations is being considered.

4.4 Mechanisms

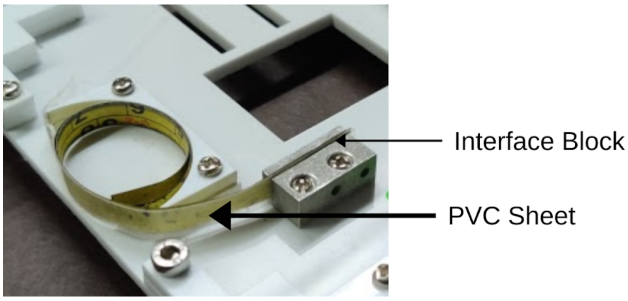
4.4.1 Antenna retention & deployment

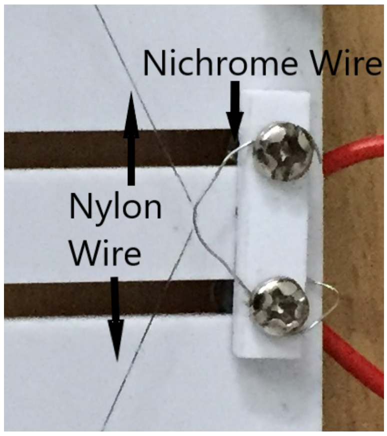
- Antenna is retained in its stowed position with the help of C-shaped subchassis, nylon thread and PVC sheet.



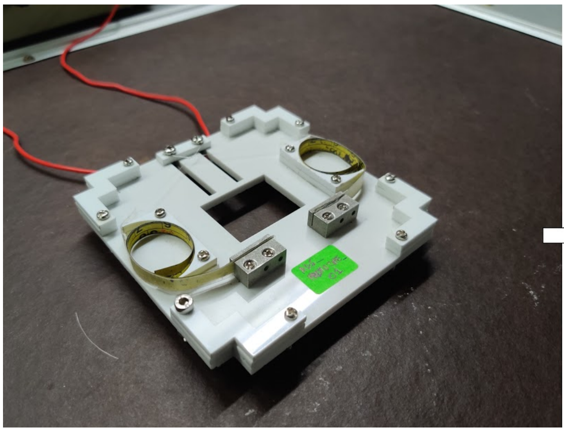
- One end of the antenna is attached to an aluminium block, along with a flexible PVC sheet as shown in Fig: xx. This block is used to interface the antenna to the tapered traces on the ADS PCB, and is henceforth in the text referred to as interface block.

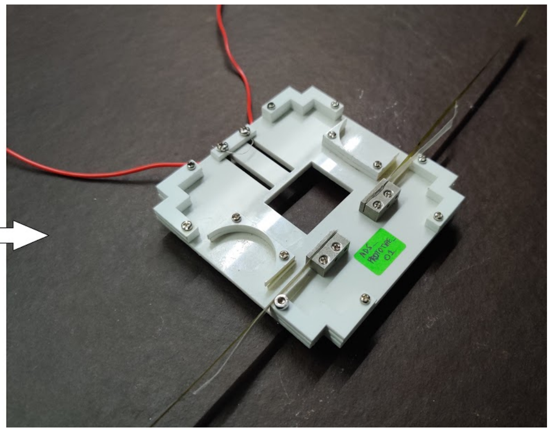
- The other end of the PVC sheet has a hole for the attachment of nylon thread. The PVC sheet passes over the coiled antenna, which in turn, is connected to the nylon wire.





- The nylon thread passes through the nichrome wire loop. The other end of the nylon thread is connected to the PVC sheet which is attached to the other interface block, such that it is in tension. This keeps the coiled antennas retained in the required stowed position.

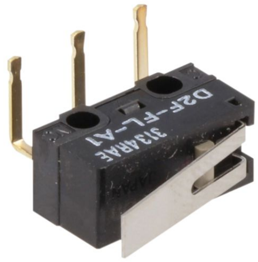




- A nichrome burn wire release mechanism is used for the deployment of the antennas. When current is passed through the nichrome wire, the nylon thread is thermally cut. This causes the strain energy present in the deformed antenna held in its coiled state to be released. Both the poles of the antenna are deployed and hence attain their straight configuration.

4.4.2 Deployment Detection

- A Single Pole Double Throw (SPDT) switch is used for deployment detection. The ADS module has two switches, one adjacent to each C-shaped chassis. The antennas press against the switches in their coiled state. When the antenna is deployed, the flap of the switch is released. This indicates that the antennas have been deployed successfully.



4.5 Thermals

4.5.1 Objectives

- All electronic components have an optimum operational range. It is important to maintain temperatures within certain limits to ensure efficient operation.
- The thermal subsystem manages the distribution of temperature of the system to ensure that the temperature level is adequate for all phases of the mission (launch, transfer orbit, operation in orbit).
- The thermal subsystem is responsible for modelling the thermal environment in space, performing thermal simulations on the system, identifying the areas with temperatures beyond the desirable range and devising appropriate methods for thermal control.
- Thermal analysis is also required to ensure the sustainability of the physical structure. Large temperature differences within the system can lead to thermal expansion or contraction, which can cause a mechanical failure.

4.5.2 Major Decisions & Developments

- A software switch from NASTRAN to ANSYS was made. ANSYS is now being used for thermal modelling and simulations. Two things were to be done - Learn ANSYS for thermals and then model an orbit in ANSYS as it does not have an inbuilt orbit modelling feature.
- After learning ANSYS, some simulations which were previously done on NASTRAN and didn't involve orbits, were performed on ANSYS and the results were compared. Initially, 2D meshing was used in NASTRAN. While comparing results from ANSYS and NASTRAN it was observed that the results generated using 3D mesh in ANSYS were not matching the simulations performed using 2D mesh in NASTRAN. Hence, simulations in NASTRAN were performed with 3D meshes for better comparison. 3D meshes were more intuitive and realistic and the results from both the softwares were close enough. From then onwards, 3D meshing was used in NASTRAN.

- ANSYS does not have an inbuilt Orbit Modeller like NASTRAN, so several papers were surveyed in search of Orbit Modelling methods. The papers gave out various codes which generated heat flux experienced by the system in the orbit. These codes needed to be tested for correctness. An error bound was established to compare the results from the simulations performed using the codes with that of the NASTRAN's orbital model. Numerous simulations were performed using various codes and a code satisfied the set criteria after required modifications. This code is currently responsible for Orbit Modelling for SANKET.
- Thermal simulations in ANSYS using shell modelling for thin objects were also explored. ANSYS allows the user to apply boundary conditions on only one side of the mid-surface created for shell modelling. Boundary conditions such as radiation are to be applied on both sides of objects. Hence, this task has been halted for the time being. For now, modelling of thin objects is being done using 3D meshes.

4.5.3 Modelling(Screw and orbit)

1. Screw Modelling
   - Screw Modelling in thermals is done to examine whether the absence of screws causes any significant variance in the results of the simulation.
   - For the verification of Screw Modelling, two simulations will be run on a test geometry, one with screws and another without them.
   - The screws used in the simulation were simple ones, with a cylindrical screw body and a flat Screw Head.
   - By seeing a difference in results, a decision will be taken on whether to model screws or not
2. Orbit Modelling
   - In an orbit, satellites mainly receive 3 types of external heat loads :
     (a) Direct Solar- Sunlight is the greatest source of heat incident on most spacecraft in Earth's orbit. The intensity of the sunlight varies, depending on the distance from the sun.
     (b) Albedo- Sunlight reflected off a planet or moon is known as albedo. The heat flux falling on a satellite due to albedo is a function of the altitude.
     (c) Earth IR- It is the heat flux emitted by our planet. Earth IR falling on a satellite is also a function of the altitude.
   - The satellite experiences different values of heat fluxes along each of its axes depending on the orientation of the satellite and the orbit in which it is placed.
   - For simulating this space environment, an orbit model is needed, so that the heat fluxes on the faces of our satellite can be calculated.

- MATLAB code was written which is inspired from a thesis [3], which models an orbit and thus gives us the values of the three types of heat fluxes for all the faces (Nadir, Zenith, Leading, Lagging, Sunside and Anti-sunside) of a satellite in an orbit.
- According to the materials of various components being used in the system, the heat flux corresponding to each material can be obtained by multiplying the values of heat fluxes with the material's emissivity(in case of Earth IR) and absorptivity(in case of Solar and Albedo).
- Then, these values should be applied on the appropriate faces of the satellite.
- For faces that are at a certain angle from the standard axes, appropriate components(trigonometric) of the heat fluxes are to be used.

4.5.4 Satellite Simulation

Satellite simulation incorporates all the aspects of modelling, simulation, boundary conditions, and orbit parameters and puts them to work in one single model.
Software: ANSYS was used for Thermal simulations of SANKET.
Model Name: SAN0010001

Material Properties:

- All the components of SANKET are assumed to be uniform and therefore thermal properties are applied to them accordingly.
- The thermal properties of FR-04 are applied to Electrical, Communication and ADS PCBs.
- All the side panels, PPOD Rails, Top and Bottom Cage, Bottom Panel and Linear Stubs are given the properties of AL-T6061.
- The detection switch was assumed to be of structural steel.
- C-sub-chassis was assigned the thermal properties of POM.

Material	**Thermal Conductivity(W/m-K)**
AL-T6061	155
FR-04	0.23
POM	0.4
Structural Steel	16.2

Simplification of Model:

For the simplification of geometry, all the screw holes are removed from the satellite and instead filled with material of the corresponding component. This has been done to reduce the number of elements formed during meshing as well as to simplify the overall meshing. This in turn helps in reducing the computational time and gives us an approximate idea about the variation of temperature over the satellite body. Thus, we can identify the regions which require extensive meshing and calculations without making the simulation more complex.

Mesh:

The default mesh generated by ANSYS was used as it is.

Contacts:

- ANSYS generates contacts automatically throughout the body.
- Contacts are essential at required places for conduction to occur so the contacts automatically defined by ANSYS need to be re-verified.

Conduction:

No Additional element/feature needs to be applied for conduction as ANSYS takes conduction at every contact and throughout the elements of the body.

Radiation:

- Radiation allows the components of the satellite to interact thermally with the components not in contact with one another as well as with the environment.
- Property of Radiation was applied to all the surfaces in the satellite body with corresponding emissivity values.
- Radiation is applied to components differently according to their interaction with the environment or any other component in the following manner:
  - If any face interacts with the space environment, 'To Ambient' radiation is applied to it.
  - If any face interacts with another face of some other component, 'Surface to Surface' radiation is applied to it. There are further 2 divisions- 'Perfect' and 'Open' enclosures. The perfect enclosure is chosen when the radiating surface is completely

separated from the other environments. The open enclosure is chosen when the radiating surface can be viewed from outside the local environment.

- The Outer faces of the Side Panels, PPOD Rails, Outer Portions of the Top and Bottom Cage, Top Panel radiate to the environment (to Ambient)
- The Inner faces of Side Panels, PPOD Rails, electrical and communication PCBs, Top and Bottom Cage, ADS PCB, bottom Panel all radiate to one another and form an open enclosure.
- The inner faces of linear stubs, detection switches, C-sub-chassis, Interface Blocks, ADS PCB were allowed to radiate to one another as well as to the environment forming another open enclosure.
- The outer faces of linear stubs radiate with the stubs extruding from the top cage forming independent open enclosures.

Orbit Setup:

- A Sun-synchronous Orbit with the following parameters was modelled:

Parameter	Value
Period	98.44 minutes
Eccentricity	0.0030
Inclination	98.1228953 degree
Right Ascension of Ascending Node	329.2442 degree
Argument of Periapsis	263.1090 degree

Zenith to Nadir :+Z axis
Leading to Lagging :+X axis
Sun side to Anti-Sun side :+Y axis

Orbital Heat Fluxes:

- Heat flux values obtained corresponding to the orbit modelled in MATLAB are applied to all the faces visible from the environment perspective.
- Heat fluxes are obtained at 15 time points in an orbit.

Boundary Conditions:

Initial Temperature: 20C
Ambient temperature: -273.00C

- **Simple Radiation to Environment**
  Every face of every component which was visible to the environment (space) has been allowed to radiate to the environment with the values of emissivity and absorptivity defined as:

Material	**Emissivity**	**Absorptivity**
AL-T6061	0.031	0.2
FR-04	0.7	0.65
POM	0.87	0.95
Structural Steel	0.14	0.47

  Radiation boundary condition is applied to all the components.

- **Temperature Constraint from PS4:**
  - Performing a simulation of SANKET on PS4OP would have been computationally very expensive. So, a decision was made to model PS4 first and then use its results as appropriate boundary conditions for the simulation of SANKET.
  - A CAD Model of PS4 was developed with some assumptions.
  - The simulation was performed in the same orbit as mentioned above.
  - The temperature of a particular point on the disc (assuming SANKET will be placed there) was recorded at various time intervals which will act as a temperature constraint for the lower face of the bottom cage of SANKET.

  Temperature constraints obtained from the PS4 simulation are applied to the lower face of the bottom panel of the SANKET.
  The heat exchange by radiation between the PS4 and SANKET and heat generation of PS4 are ignored for now, but it will be in further simulations if they are appreciable.

  Heat Load from various components on the PCBs:
  Heat flow values of various components are taken from the Power Budget of SANKET:

Components	**Heat Load**(mW)
SVRMC28 (EMI Filter)	2400
SVRHF283R3S (Voltage Regulator)	2508
ATmegaS128	80
TPS7H2201-SP (Current Limiter)	450
CC1125 (Transceiver)	168
MAAM-011229 (LNA)	72
CMX901 (HPA)	2161
TPS50601A-SP (Voltage Regulator)	453

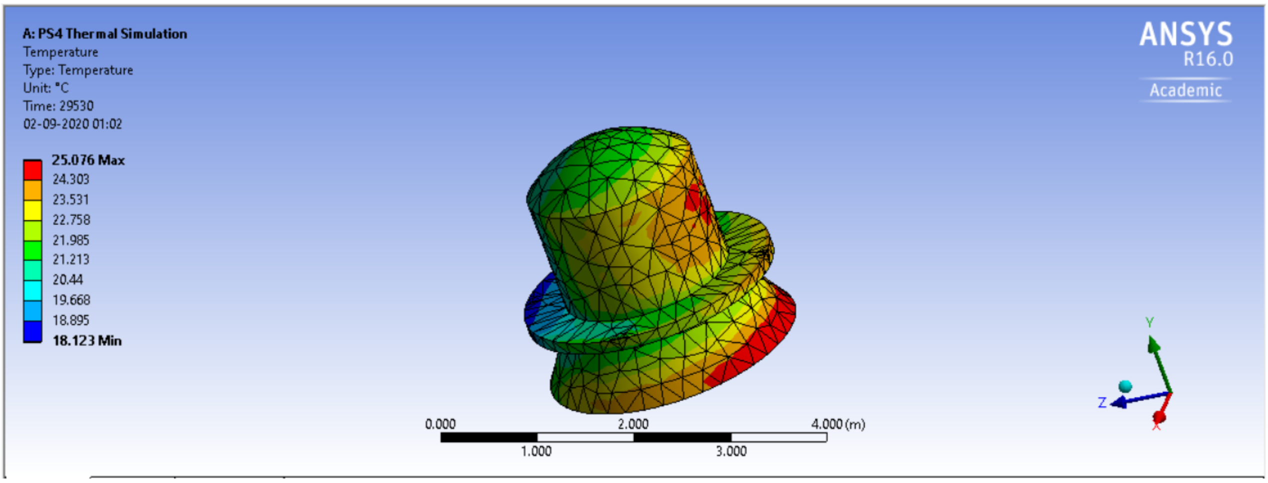


Figure 4.15: PS4 Simulation Results

The simulation is run for 3 orbits.

4.5.5 Results

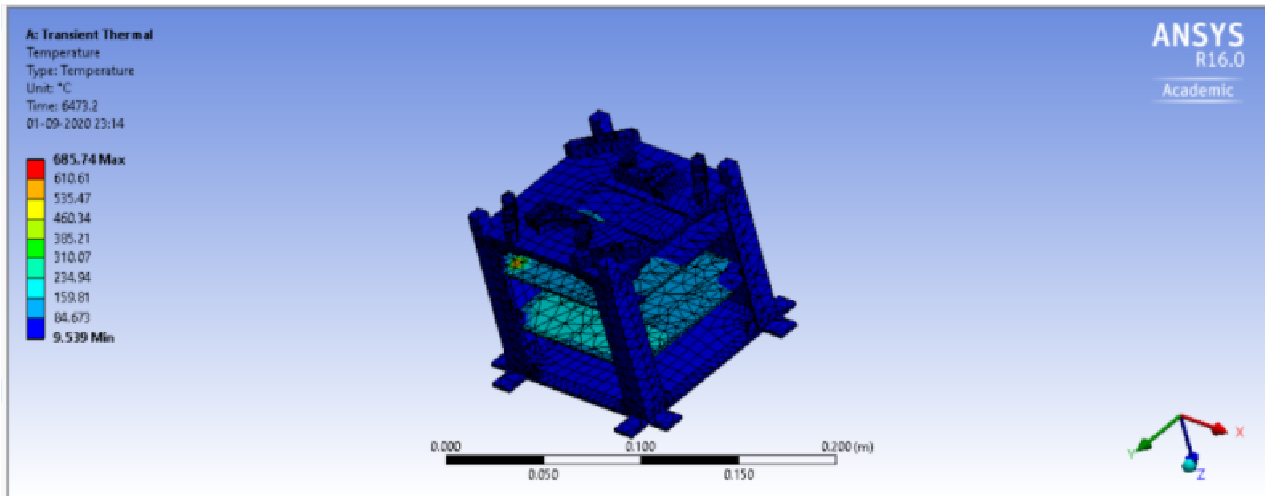


Figure 4.16: SAN0010001 Simulation Results

- After running the simulation for 3 orbits, a maximum temperature of 685 C was recorded on the communication PCB at the High Power Amplifier. This temperature is unusually high as there is a large heat load applied on a small area.
- The other components of the PCBs recorded a temperature ranging from 100 C-200 C. This lies outside the operating range of the components.
- The temperature on ADS PCB was in the range of 15 C-25 C
- Thus, the system would require thermal control.

- Also, there is a chance that the modelling of components might be done in the wrong way.

4.5.6 Passive Thermal Control

Passive thermal control requires no input power for thermal regulation within a spacecraft. It involves no mechanical moving parts or fluids. Passive thermal control systems generally have low cost, volume, weight and risk.
The following methods of passive thermal control have been explored by the team. The appropriate methods will be chosen after thorough analysis of the simulation results.

- Multi Layer Insulation
  They are utilized to reduce heat loss from a spacecraft to the surroundings when the satellite is in its orbit. The principle of an MLI blanket is to use multiple layers of radiation shields to reflect back a large percentage of the radiant heat flux reaching each radiation shield in the opposite direction of heat flow.
- Surface Coating
  Surfaces can be modified to emit and absorb energy at specific rates. This can be done by altering their optical properties(emissivity and absorptivity). Thermal coating can be done in various forms- paint, thermal tapes, metallic coatings, etc. The appropriate method of coating is to be chosen on the basis of the mission life and the rate at which the coating degrades in the orbit due to atomic oxygen and delamination of bonded materials.
- Optical Solar Reflectors(OSR)
  An optical solar reflector is a second surface mirror with low absorptivity/emissivity ratio. It is typically used on the sun-side of the satellite to protect it from solar radiations.
- Phase Change Material
  Phase change materials are used as a heat sink/source for electronic components used in the satellite. When the temperature of the component is high, the phase change material melts and stores thermal energy. Later, when temperatures are lower, it releases this energy to convert back into solid form, hence maintaining temperature.

4.6 Manufacturing

4.6.1 Modelling

- If an edge is not critical then it must be done fillet with the radius as same as the radius of the tool(radius between 0.5mm to 1mm) since increasing tool radius saves money and time as well. If the fillet is not provided then the vendor takes that edge as critical and uses fine machining which has a higher cost and more time-consuming.

- At all the mating sites of components, wherever there is some fillet on some component on some edge we need to make a chamfer on another component to avoid Interference.

4.6.2 Material and Methods

The parts of the system that have been manufactured and the processes involved are as follows:

- Antenna:
  It is made by using tape spring which is made up of steel. After buying the tape spring from the market, the first step of converting it into an antenna is washing off the paint from the tape spring. The tape spring is kept in Isopropanol for at least 1-2 days for easy removal of paint using sandpaper. The required dimension of the antenna in our case is 18cm*6mm*0.5mm. A strip of nearly 25cm in length is given to the manufacturer who uses the method of wire EDM to convert it into the required dimensions. The width of the tape is brought to 6mm by removing the material from the edges along the width. Then, the holes are drilled to make an interface with the interface block.
- C-Subchassis:
  It is made from POM(Polyoxymethylene). A larger block of POM is converted into the required dimensions and the C shape by using CNC machining. A Zn based paint is applied on the POM block so that there is no accumulation of static charges when it is in lower earth orbit.
- Interface Block:
  It is made from Al6061-T6. A larger block of Al6061-T6 is converted into the required block of given dimensions using wire EDM and the holes for interfaces are made by drilling.

4.6.3 Prototyping

Several prototypes of the ADS(Antenna Deployment System) were designed for the following objectives :

- Better visualization of all the components assembled together evolving into the ADS.
- Ideating and testing antenna retention techniques.
- Testing of the Burn-wire mechanism developed for antenna deployment.

The specifications of the latest prototype are as follows :

- The prototype was manufactured from Acrylic, except for the Interface Blocks which were made out of Aluminium.
- Laser cutting was used for cutting the Acrylic sheet of 3mm thickness into various components.
- Tape spring was chosen as the material for antenna fabrication due to less residual bending strain as compared to beryllium copper.
- The antenna was manufactured using the Wire-EDM technique. The dimensions of both poles being 180mm X 6mm X 0.5mm.
- The antenna is held in place with the help of interface blocks.
- The antenna is coiled and stored in the C-sub-chassis with the help of nylon thread and PVC film. The nylon thread is further connected to the burner circuitry.

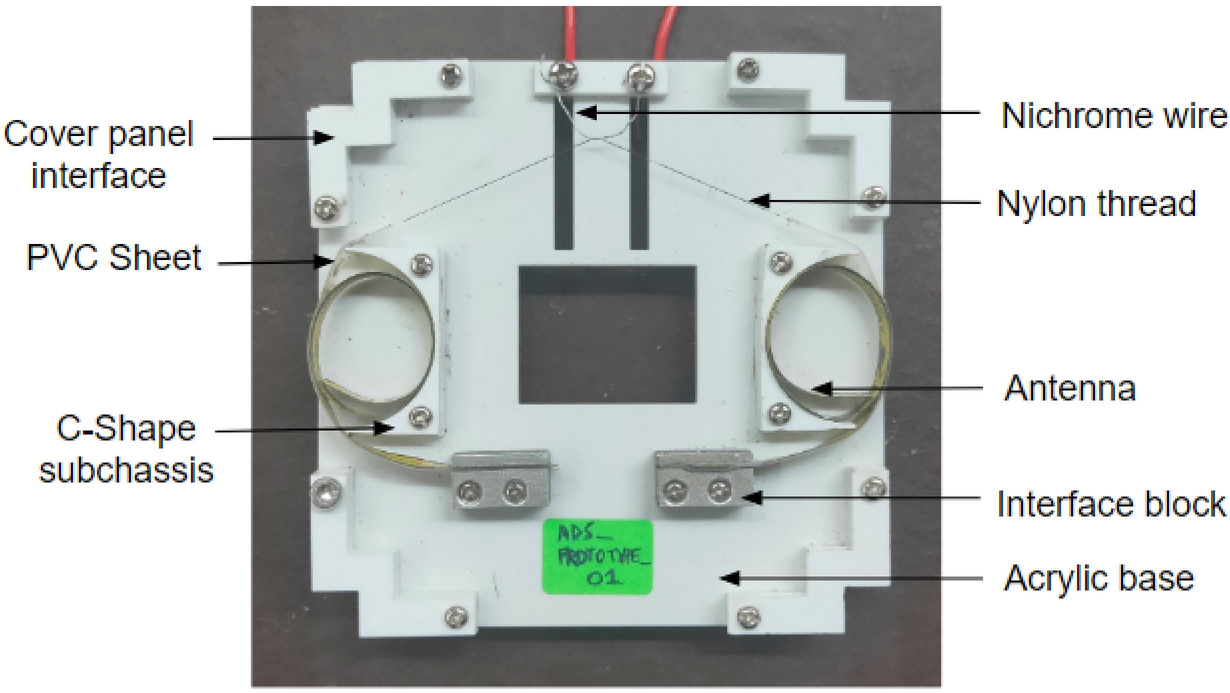


Figure 4.17: ADS Prototype

4.6.4 Vendor List

4.7 Integration

4.7.1 Interface Control Document(ICD)

This Interface Control Document is for SAN0010001 as given in the QA section of the document.

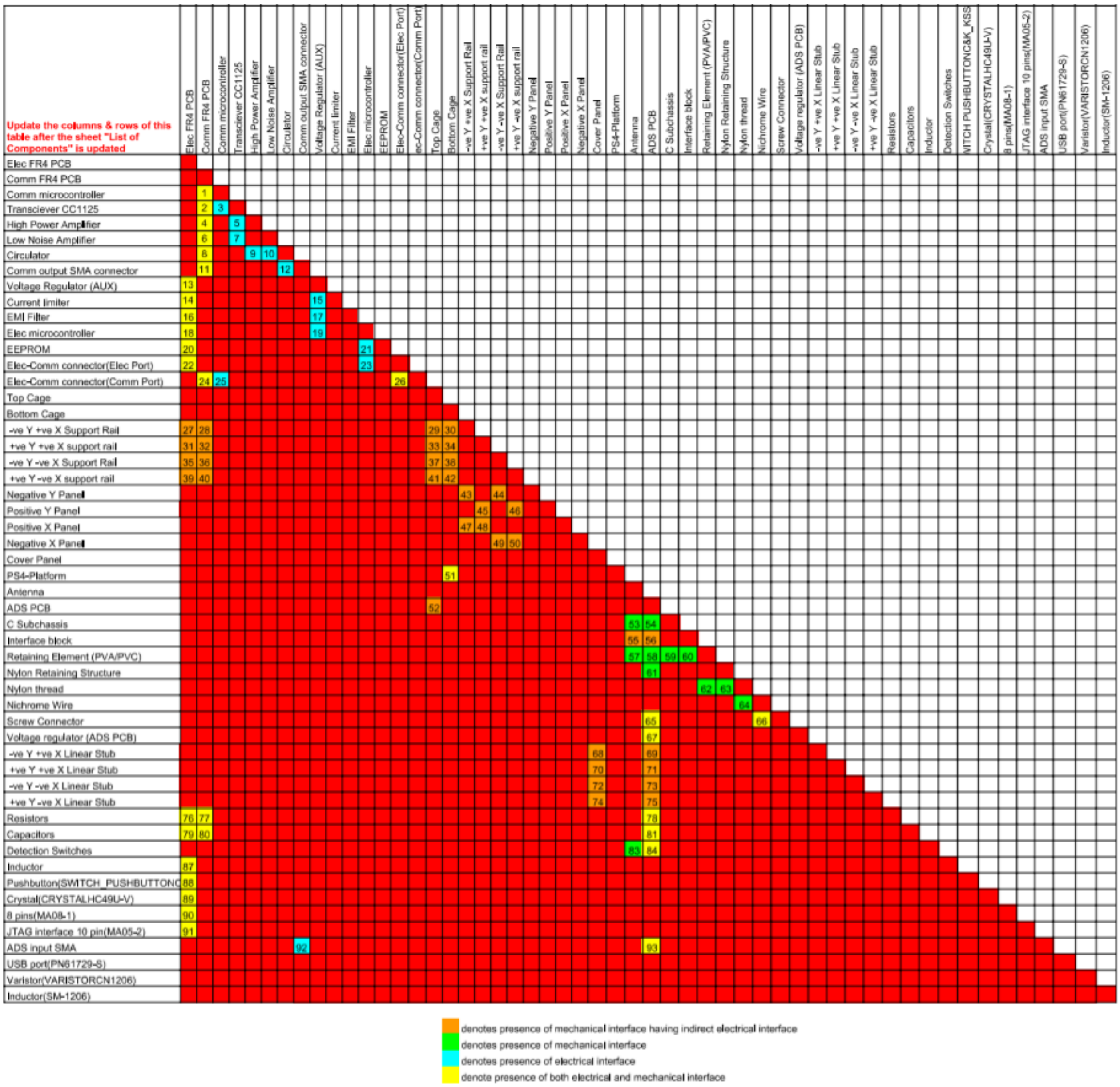


Figure 4.18: Sanket ICD

The table given below gives the information regarding the interfaces of the main mechanical components in the ICD. Rest of the components can be found in the electrical part.

Interface ID	Component 1	Component 2	Nature of Interface	
			Mechanical	**Electrical**
27	-ve Y +ve X Support Rail	Elec FR4 PCB	Screw	Ground
28	-ve Y +ve X Support Rail	Comm FR4 PCB	Screw	Ground
29	-ve Y +ve X Support Rail	Top Cage	Screws	Ground
30	-ve Y +ve X Support Rail	Bottom Cage	Screws	Ground
31	+ve Y +ve X support Rail	Elec FR4 PCB	Screw	Ground
32	+ve Y +ve X support Rail	Comm FR4 PCB	Screw	Ground
33	+ve Y +ve X support Rail	Top Cage	Screws	Ground
34	+ve Y +ve X support Rail	Bottom Cage	Screws	Ground
35	-ve Y -ve X Support Rail	Elec FR4 PCB	Screw	Ground
36	-ve Y -ve X Support Rail	Comm FR4 PCB	Screw	Ground
37	-ve Y -ve X Support Rail	Top Cage	Screws	Ground
38	-ve Y -ve X Support Rail	Bottom Cage	Screws	Ground
39	+ve Y -ve X support Rail	Elec FR4 PCB	Screw	Ground
40	+ve Y -ve X support Rail	Comm FR4 PCB	Screw	Ground
41	+ve Y -ve X support Rail	Top Cage	Screws	Ground
42	+ve Y -ve X support Rail	Bottom Cage	Screws	Ground
43	Negative Y Panel	-ve Y +ve X Support Rail	Screws	Ground
44	Negative Y Panel	-ve Y -ve X Support Rail	Screws	Ground
45	Positive Y Panel	+ve Y +ve X support Rail	Screws	Ground
46	Positive Y Panel	+ve Y -ve X support	Screws	Ground

		Rail		
47	Positive X Panel	-ve Y +ve X Support Rail	Screws	Ground
48	Positive X Panel	+ve Y +ve X support Rail	Screws	Ground
49	Negative X Panel	-ve Y -ve X Support Rail	Screws	Ground
50	Negative X Panel	+ve Y -ve X support Rail	Screws	Ground
51	PS4-Platform	Bottom Cage	Screws	-
52	ADS PCB	Top Cage	Screws	Ground
53	C Subchassis	Antenna	Mechanical	-
54	C Subchassis	ADS PCB	Adhesive +Screw	-
55	Interface block	Antenna	Screws	Feed
56	Interface block	ADS PCB	Screws	Feed
57	Retaining Element	Antenna	Mechanical	-
58	Retaining Element	ADS PCB	Mechanical	-
60	Retaining Element	Interface block	Screws	-
61	Retaining Subs	ADS PCB	Nut-Bolt	-
62	Nylon thread	Retaining Element	Mechanical	-
63	Nylon thread	Retaining Subs	Mechanical	-
64	Nichrome Wire	Nylon thread	Mechanical	-
65	Screw Connector	ADS PCB	Screws	Power
66	Screw Connector	Nichrome Wire	Screws	Power
68	-ve Y +ve X Linear Stub	Cover Panel	Screws	Ground
69	-ve Y +ve X Linear Stub	ADS PCB	Adhesive	-
70	+ve Y +ve X Linear Stub	Cover Panel	Screws	Ground
71	+ve Y +ve X Linear Stub	ADS PCB	Adhesive	-
72	-ve Y -ve X Linear Stub	Cover Panel	Screws	Ground
73	-ve Y -ve X Linear Stub	ADS PCB	Adhesive	-
74	+ve Y -ve X Linear Stub	Cover Panel	Screws	Ground
75	+ve Y -ve X Linear Stub	ADS PCB	Adhesive	-
83	Detection Switches Stub	Antenna	Mechanical	Ground
84	Detection Switches	ADS PCB	Nut-Bolt	Power

	Stub			

4.7.2 Bolt Preload

Objective :- To find fasteners and the optimal preload(torque) that should be applied to reduce the chances of failure to all the joints.

Definition of preload:- The clamping tension created when the nut is screwed onto a bolt to hold two materials together.

Importance of the task:- The proper amount of torque which in turn produces a preload inside the bolt is very important. Without bolt preload, the entire structure would be totally reliant on the bolt to hold the weight. With proper bolt preload, the external load is distributed properly between bolt and the joints which reduces the chances of bolt failure or separation.

Relation between torque and preload is given by, T = $K_T * d_{nom} * P$ where T is torque, K_T is the torque coefficient, d_{nom} is the nominal diameter of the bolt and P is the amount of preload created by the given torque.

Torque coefficient K_T is a factor applied to account for the effects of friction in the torquing elements like bolt and nut. The calculation for each case is pretty complex, so we can use the value of 0.2 which is experimentally verified.

Preload uncertainty:- Due to various effects such as uncertainty created by torquing instruments, thermal loading, preload relaxation over time etc, the initial preload can change to a different value. Combining all factors for a manually torqued, lubricated fastener with negligible thermal effects, it can be assumed that the preload lies between $P_{max} = 1.25 * P$ and $P_{min} = 0.714 * P$.

To find the optimal amount of torque that needs to be applied, calculation of optimal preload is required.

Subtask 1 :- Calculation of optimal preload and torque

In a paper regarding preloaded joint analysis by NASA , it is mentioned that the preload can be assumed to be 65 percent of the tensile yield strength of the bolt material but the value isn't optimal. To find the optimal preload, simulation is done on a preloaded model.

The model is mechanically simulated in two steps. In the first step, the loads applied on the model are only the preload on the bolts. In the second step, the external loads such as acceleration are applied. The stresses are compared between time,t=1 and t=2. Then, an analysis is conducted to find at what amount of applied preload, the lowest percentage of external load is getting applied on the bolt rather than getting distributed in the joints. The same steps are followed for different amounts of preload and the optimal preload is found.

Simulations on a bolt preloaded CAD model

- Software used: Ansys
- Model Name: BTP0010001

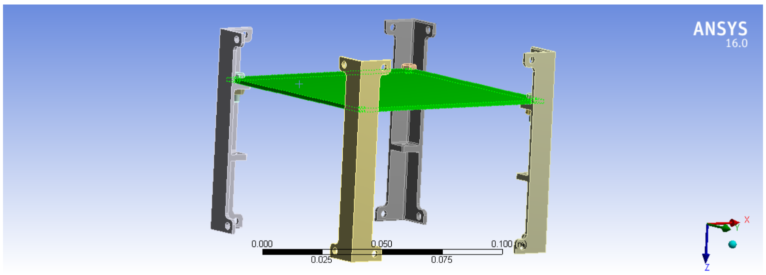


Figure 4.19: BTP0010001

Component	Material	Young's Modulus
Support Rail	Al-6061 (T6)	69 GPa
PCB	FR4	(Ex, Ey, Ez)= 20.4 GPa, 18.4 GPa, 15 GPa
M3 Bolt and Nut	Al-6061 (T6)	69 GPa

Table 4.13: Material properties

- Symmetry: The given model is symmetrical along two planes as seen in the given figure. The static loads are also the same along the x and y axis. So, symmetry is used and the model is divided into 1/4th to reduce the no. of nodes and the computational load on the computer.

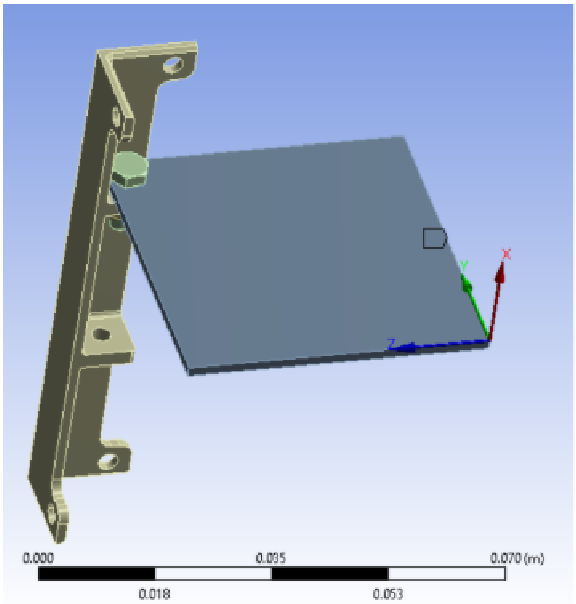


Figure 4.20: Symmetric Model

Note:- Symmetric model not to be used in dynamic simulations(modal, harmonic and random in our case)

- Mesh: Body sizing with four spheres of influence of radius 3.5E-03m and element size of 4.4E-04m. (A mesh convergence study was conducted on the model but the values of stress didn't converge as the size of the mesh became smaller. This was due to stress singularity in post processing. The maximum stress values were fluctuating a lot and not converging. Therefore, the average stress was considered around the bolt where the maximum stress occurs. Then, the convergence was found at the element size equal to 4.4E-04m.)

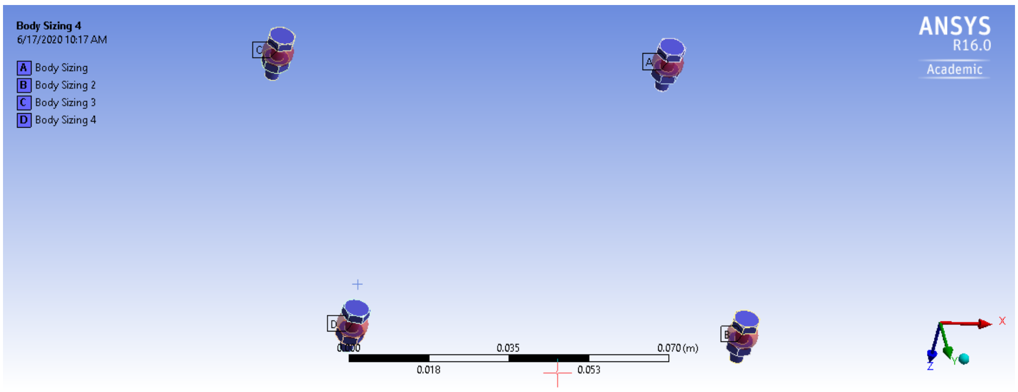


Figure 4.21: Spheres of influence

- Contacts:
  Bonded contact between lower cylindrical surface of bolt with nut No separation contact between lower surface of PCB and upper surface of support rail, upper cylindrical surface

of bolt with PCB, upper surface of bolt with lower surface of support rail, upper surface of PCB with lower surface of bolt head.

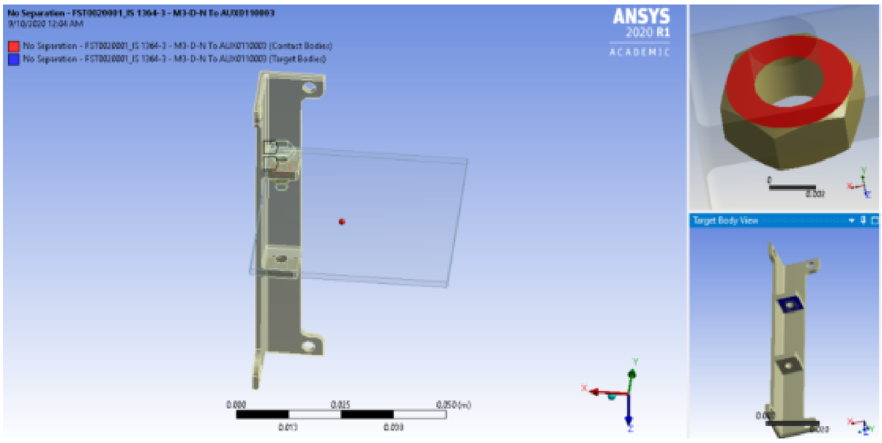


Figure 4.22: No separation joint between nut and support rail

- Fixed Support: Base of support rails

Simulation 1

Load Application Step 1 (t=1): Bolt Pretension of variable values starting from yield strength times nominal area to 0 N.

Load Application Step 2 (t=2): Acceleration loads of 6g in lateral direction and 7g in the axial direction.

Here Multiple step inputs are done using changes made in analysis settings and also giving inputs for load in tabular data such that other load is 0 in that step.

Details of "Analysis Settings"

Step Controls	
Number Of Steps	2.
Current Step Number	1.
Step End Time	1. s
Auto Time Stepping	On
Define By	Substeps
Initial Substeps	1.
Minimum Substeps	1.
Maximum Substeps	10.

Results:- The stress difference observed in the model between the time t=1 and t=2 is very much insignificant to analyse the results because bolt pretension loads are very high compared to acceleration loads.

A significant difference in the stress at these times can be observed only when bolt pretension is below 100N.

Simulation 2
This simulation is done in two different environments. One which doesn't have any loads initially and another is a pre-stressed modal simulation which has bolt pretension=650N in it initially.
Results:- The frequencies of all the respective nodes between the two simulations get increased in the second case compared to the first. For example: the frequency of first mode is increased from 265 Hz to 424 Hz when bolt pretension is applied initially.

Simulation 3
This simulation is also done in two different environments. One which takes the first modal simulation solution as a setup which is conducted without any loads initially. The other one is done in which the second modal simulation solution is taken as the setup for this simulation. The frequency range here is 8-200 Hz with 20 solution intervals.
Results:- The stress increased as the frequency increased in both the cases. The stresses were significantly higher for the second case for each frequency compared to the first case.

Note:- Many other simulations were conducted too such as replacing the bolt with a line body to minimize the computation required. Bolt preload was applied on the line body but the results weren't matching and many problems were appearing in the modal simulation as well. Random and Harmonic simulations on this model were also getting more and more complicated.

Inference:
The above simulations could not be used for our purpose of completing the task which is to calculate the optimal preload because the preload is usually very high compared to external static loads experienced by the satellite and there is usually zero or very less difference in the stress between time intervals.
The equivalent stress developed in the vibration simulation is quite high and thus would have been a primary factor for deciding optimum value of bolt preload. Doing random simulations on a preloaded model requires many other inputs and processes such as design assessment ,which involves APDL coding, and load combination which needs to be theoretically understood and analysed. Therefore, the preload is taken as 66.7% of yield strength times the tensile stress area. The value is taken as such by looking into Shigley's Mechanical Design which mentions that many studies were conducted and %yld=66.7% can be used. So, the preload F_{pl} is given by, F_{pl}=$\%yld * S_{ty} * A_t$.
Tensile Stress Area(At):- The cross section area of an unthreaded rod having the same tensile strength as a threaded rod with nominal diameter, d_{nom}. The formula for tensile stress area is $A_t = \pi/4 * (d_{nom} - 0.9382P)^2$, where P is the pitch of the threaded rod.
In our case, the material used is stainless steel (SS-304) with tensile yield strength, S_{ty}= 215

MPa.

Type of Bolt	Tensile Stress Area (mm^2)	Optimal Preload (N) F_{pl}	Torque (N-m)	Maximum Preload (N) $1.25 * F_{pl}$	Minimum Preload (N) $0.714 * F_{pl}$
M2*0.4	2.073	381.6	0.153	477.0	272.5
M3*0.5	5.031	926.2	0.556	1157.7	661.3
M4*0.7	8.779	1616.1	1.293	2020.2	1153.9
M6*1	20.12	3703.9	4.445	4629.9	2644.6

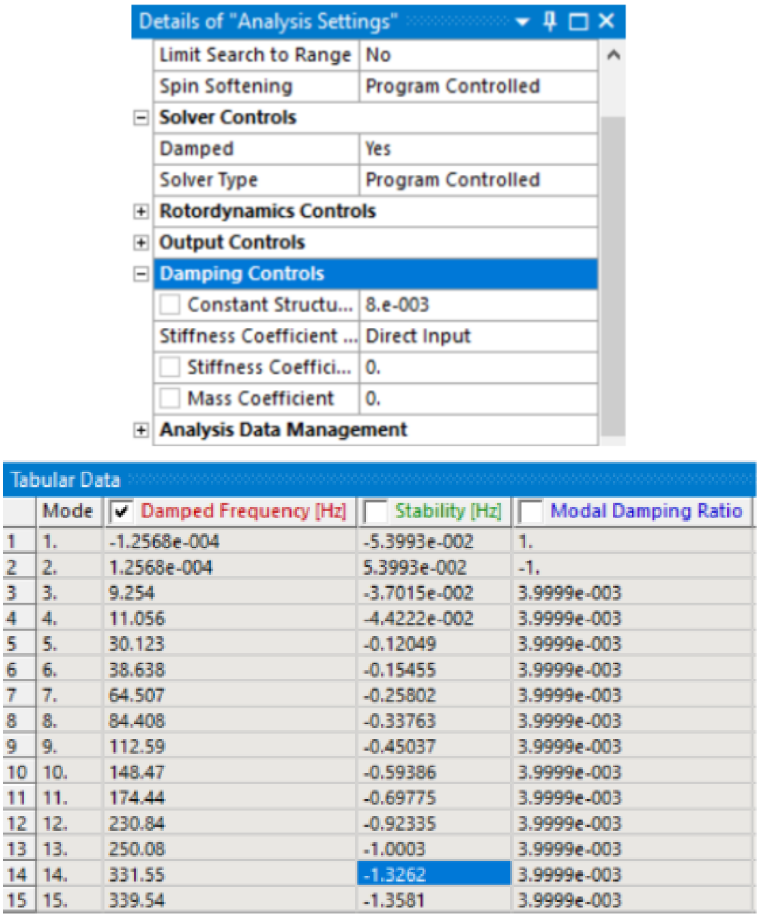
Table 4.14: Torque and bolt preload values

Verification of pre-stressed Modal and Random Vibration in ANSYS

- Prestressed Random and pre-stressed vibration take in effect of the combined effects of static and dynamic loads. For verification setup and simulation were compared from Random response analysis of pre-stressed structures using MSC/NASTRAN and theoretical results for vibration of a linear material beam from section 10.2.2 of MSC/NASTRAN Handbook for Nonlinear Analysis, Version 67, The MacNeal-Schwendler Corporation, Los Angeles, CA, November 1988.
- Setup
  - Material Properties- 68.65 GPa(modulus of elasticity), 0.3(Poisson ratio), 2700 Kg/m^3(density), 0.04(modal damping ratio).
  - Dimension - 1.0m*0.003m*0.004m
  - Fixed Support- The Beam was to give simple support at 2 ends. For this, Nodal Displacement of the centre of 2 faces in axial direction was kept to free and 0 for other perpendicular directions. Another option would have been to keep the face deformable and apply the displacements at both faces of the beam.
- Results - Theoretical formulae

  $$\omega_n = (n\pi)^2\sqrt{\frac{EI}{mL^4}} \qquad \omega_n = (n\pi)^2\sqrt{\frac{EI}{mL^4}\left(1 + \frac{1}{(n\pi)^2}\frac{PL^2}{EI}\right)}$$

  where P is a constant axial force on a beam. All results theoretically and from paper for modal simulation with varying values of P =0N, 0.01N, 5N were found to be exactly matching.



Details of "Analysis Settings"

Limit Search to Range	No
Spin Softening	Program Controlled
Solver Controls	
Damped	Yes
Solver Type	Program Controlled
Rotordynamics Controls	
Output Controls	
Damping Controls	
Constant Structu...	8.e-003
Stiffness Coefficient ...	Direct Input
Stiffness Coeffici...	0.
Mass Coefficient	0.
Analysis Data Management	

Tabular Data

	Mode	Damped Frequency [Hz]	Stability [Hz]	Modal Damping Ratio
1	1.	-1.2568e-004	-5.3993e-002	1.
2	2.	1.2568e-004	5.3993e-002	-1.
3	3.	9.254	-3.7015e-002	3.9999e-003
4	4.	11.056	-4.4222e-002	3.9999e-003
5	5.	30.123	-0.12049	3.9999e-003
6	6.	38.638	-0.15455	3.9999e-003
7	7.	64.507	-0.25802	3.9999e-003
8	8.	84.408	-0.33763	3.9999e-003
9	9.	112.59	-0.45037	3.9999e-003
10	10.	148.47	-0.59386	3.9999e-003
11	11.	174.44	-0.69775	3.9999e-003
12	12.	230.84	-0.92335	3.9999e-003
13	13.	250.08	-1.0003	3.9999e-003
14	14.	331.55	-1.3262	3.9999e-003
15	15.	339.54	-1.3581	3.9999e-003

Figure 4.23: Analysis settings for the simulation

Case of Load	Analytical Solution		
	P=0N	P=0.01N	P=5N
Modal Frequency (Hz)	6.85944	6.86507	9.25377
	9.14592	9.15014	11.0557
	27.4378	27.4434	30.1190
	36.5873	36.5879	36.6353

Table 4.15: Result of the modal simulation

- Damping in modal- For input in Constant Structural Damping Coefficient =0.008 and the output modal damping ratio of 0.004 was obtained for all accepted damping frequencies.

- Conclusion - Thus, Modal simulation on a prestressed model ANSYS is done and verified. But for random simulation, input load was Pressure PSD which is not found by default in ANSYS, but was found in ANSYS store. Direct method of linking prestressed modal with random simulation was proven to work in MSC nastran, while for ANSYS its help section also suggests that the linking only works for Harmonic and Modal Simulations.

Load combination and Design assessment were some other methods suggested by some experts on ansys forums and these can be explored next.

Subtask 2 :- Theoretical analysis of preloaded joint analysis

Some of the important things to analyse a preloaded joint are:-

1. Joint Diagram:- It is a graph of load v/s deflection of both the bolt and joint. To understand the basics of a joint diagram ,please refer this.

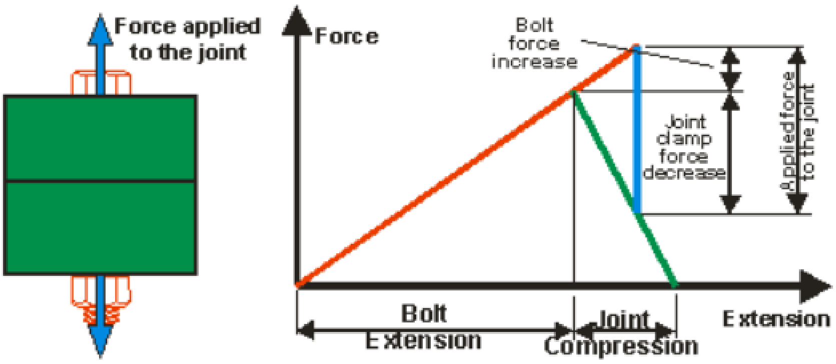


Figure 4.24: Joint diagram

In the above graph, the point where the green and red lines meet, that is the initial preload in the bolt and the joint. It can be seen that when external force is applied, the bolt force increases and the joint clamp force decreases. So, there is a need to make sure that bolt force does not increase beyond its yield strength or the joint clamp force doesn't get 0 in which the bolt will get separated.

2. Fastener Axial Load:- The total axial load in a fastener consists of the preload plus that portion of the external mechanical load not reacted by the joint. The total axial bolt load can be given by
$P_b = P_{0,max} + (SF * n * \phi * P_{et})$
where,
   - $P_{0,max}$ is the maximum preload in the bolt
   - SF is the safety factor
   - n is the loading plane factor which can be described as
     n = distance between loading planes/ total thickness of joint
     A loading plane is the plane containing the point where the total external force can be taken as an equivalent point force. To understand it properly an analogy between the joint and springs can be used.

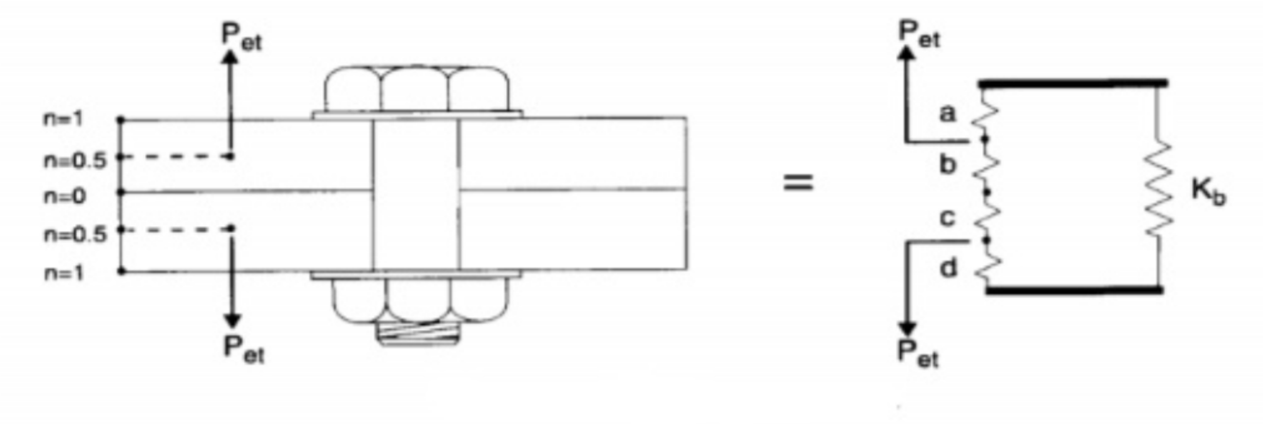


Figure 4.25: Joint and spring analogy

In the given figure, If an external tensile load, P_{et}, is introduced very near the contact surface between the two flanges (n≅0),then both flanges are further compressed through almost their entire depth.
If (n=0.5), As the external load is applied, springs b and c are relieved (unloaded) of some of their compression while springs a and d are further compressed (loaded). The compressive deflection relieved in springs b and c is partly offset by the additional compressive deflection gained in springs a and d.

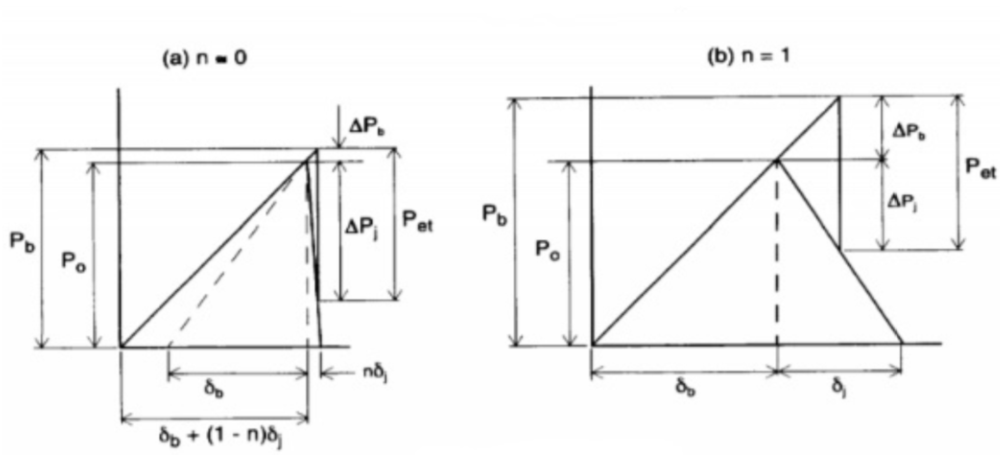


Figure 4.26: Effects of loading plane

For different n and same external load, the change in loads in bolt and joint vary by a lot. Therefore, n is a very important factor in analyzing a preloaded joint.

- ϕ is the joint stiffness factor which determines the proportion in which the load is shared between bolt and joint. The stiffness factor can be defined as:-
  $\phi = K_b/(K_b + K_j)$
  where, K_b is the axial stiffness of a circular rod with a cross section based on the nominal bolt diameter and K_j is the stiffness of the flange region which experiences the compressive preload.

- P_{et} is the external load applied.

3. Change in fastener axial load is given by, $\Delta P_b = n * \phi * P_{et}$
For the derivation, please refer here.

Subtask 3 :- Calculation of local external load
To find the fastener axial load and its change, local external load is required. A feature called reaction force in ansys can be used to find out the external force at the required surfaces in a simulation which has acceleration loads as input. This feature allows post-processing on a conducted simulation but the feature can't be used at the required surfaces in the random simulation at which the highest external force gets applied.

Subtask 4 :- Determining parallel configurations and calculations of MOS and safety factors for each
There are mainly four configurations for our consideration.

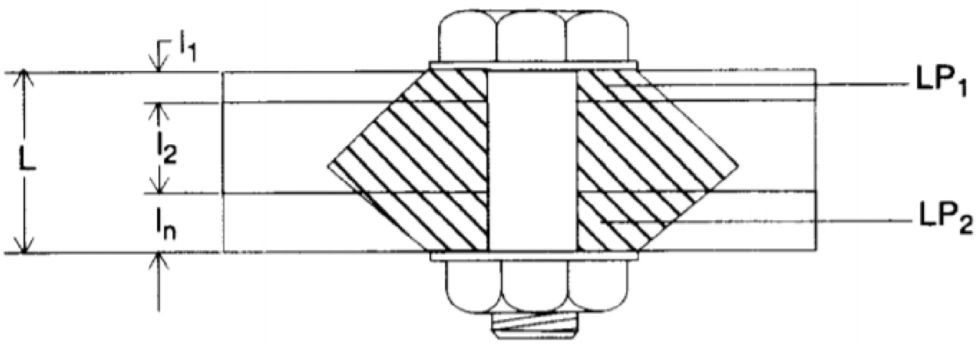


Figure 4.27: Configuration 1

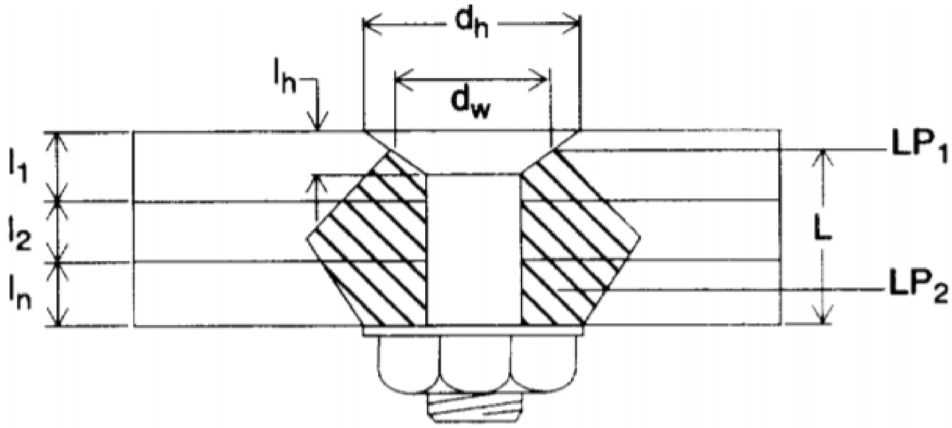


Figure 4.28: Configuration 2

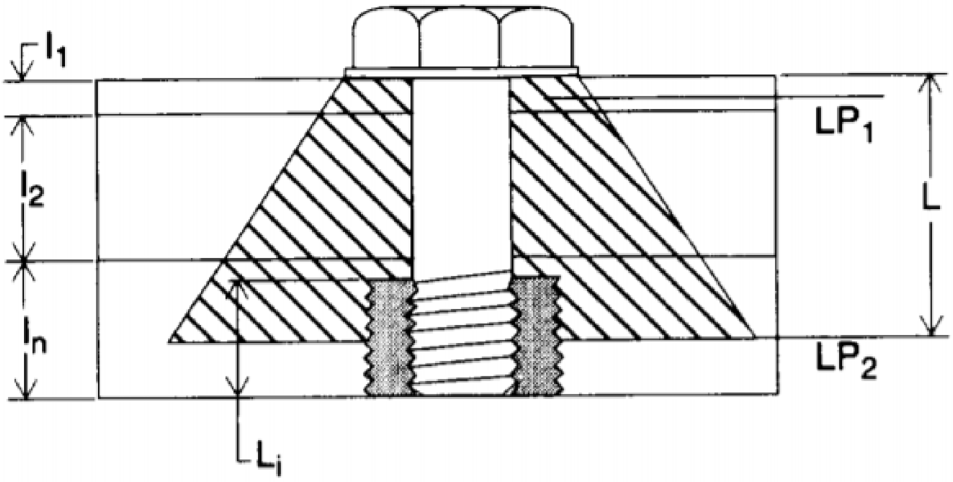


Figure 4.29: Configuration 3

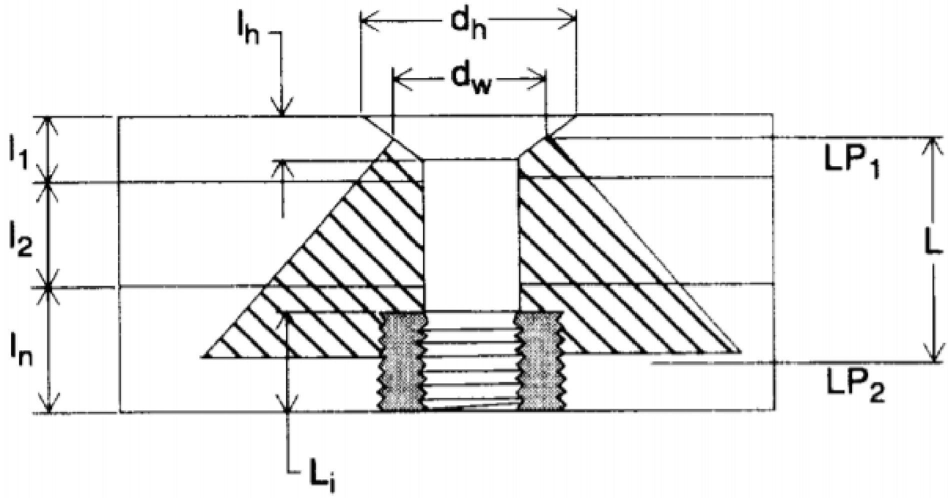


Figure 4.30: Configuration 4

To choose from the above configurations for each joint, safety factors and integrability must be considered and the one with lesser chances of failure must be chosen. Fastener Strength Criteria :- In general, for preloaded joints to work effectively they must meet (at a minimum) the following criteria:-

- Bolt(s) and joints must have adequate strength.
- Joint must not experience separation under loading.
- Bolt(s) must have adequate fracture and fatigue life.

Only two criterias are going to be looked into as of now because the third one requires dynamic and cyclic loading. For the first two criterias the margins of safeties(MoS) are used. There are many MOSs like Tension Only Criteria and Joint Separation Criteria and many others as well which will be considered later as they account for the shear as well.

1. Tension Only Criteria:
   MoS = $(TensionAllowable/P_b) - 1$

2. Joint Separation Criteria:

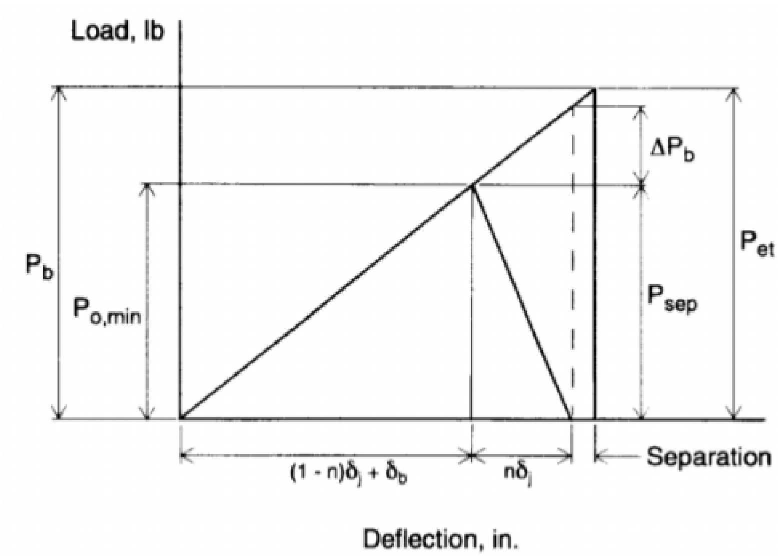


Figure 4.31: Joint separation effect

As seen in the graph, separation happens after a while clamp force is 0. Once the joint separates, the flanges cannot contribute to the load carrying capability of the connection, and the bolt is left to carry all of the external loading.
The margin of safety for joint separation can then be given as MoS= $P_{0,min}/(SF_{sep} * P_{sep}) - 1$
Where, $P_{sep} = \Delta(j) = (1 - n * \phi)P_{et}$
The recommended factor of safety for joint separation, SF_{sep}, is equal to 1.2 for structural applications.

Calculation of n, ϕ for each configurations and each joint
Various formulae are used to calculate n, phi values for each of the configurations. For all the formulae, please refer here.

Joint No.1 | Layers in order = Al6061-T6(4mm)+FR4(1.6mm) | Total Length=5.6 mm | M2							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
1	5.60	5.60	0.50	108.22	34.01	94.04	0.27
2	5.60	5.00	0.75	121.20	32.06	302.22	0.21
2 with first layer= 6mm	7.60	7.00	0.82	86.57	36.66	97.37	0.38
1 in reverse	5.60	5.60	0.50	108.22	34.01	94.04	0.27
3 in reverse	5.60	3.60	0.50	168.34	26.54	137.50	0.28
3 with first layer= 6mm in reverse	7.60	4.60	0.50	131.74	30.64	150.49	0.23

Joint No.2 | Layers in order = POM(5mm)+FR4(1.6mm) | Total Length=6.6 mm | M2							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
1	6.60	6.60	0.50	91.82	4.53	11.98	0.44
1 in reverse	6.60	6.60	0.50	91.82	4.53	11.98	0.44
2	6.60	6.00	0.79	101.00	4.63	43.65	0.55
1 with radius=M2.5	6.60	6.60	0.50	143.47	4.53	15.92	0.45
2 with radius=M2.5	6.60	5.85	0.77	161.86	4.66	57.35	0.56
1 with radius=M3	6.60	6.60	0.50	206.60	4.53	20.22	0.46
2 with radius=M3	6.60	5.78	0.75	236.11	4.68	93.37	0.54

Joint No.3 | Layers in order = Al6061-T6(6.5mm)+Tape(0.5mm)+Al6061-T6(2mm) | Total Length=9 mm | M2							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
1	9.00	9.00	0.53	67.34	69.00	170.20	0.15
2	9.00	8.40	0.82	72.15	69.00	441.13	0.12
1 in reverse	9.00	9.00	0.53	67.34	69.00	170.20	0.15
3 in reverse	9.00	5.75	0.53	105.39	69.00	325.36	0.13

Joint No.4 | Layers in order = Al6061-T6(1mm)+Al6061-T6(7mm)+FR4(1.6mm)+Al6061-T6(5mm) | Total Length=14.6 mm | M3							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
3	14.60	12.10	0.79	112.77	46.75	314.65	0.21
3 with last layer= 1.5 mm	11.10	10.35	0.89	131.84	44.33	304.76	0.27
1 with last layer= 1.5 mm	11.10	11.10	0.89	122.93	37.62	145.24	0.41

Joint No.5 | Layers in order = Al6061-T6(7mm)+FR4(1.6mm) | Total Length=8.6 mm | M3							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
1	8.60	8.60	0.50	158.66	41.32	170.35	0.24
2	8.60	7.78	0.81	175.50	39.66	519.22	0.20
3 in reverse	8.60	5.10	0.50	267.55	24.51	193.13	0.29

Joint No.6 & 7 | Layers in order = Al6061-T6(1.5mm)+Al6061-T6(1.5mm) | Total Length=3 mm | M3							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
3	3.00	2.25	0.50	606.45	69.00	709.36	0.23
4	3.00	1.45	0.48	941.04	69.00	811.06	0.26
3 with last layer= 3.5 mm	5.00	3.25	0.50	419.85	69.00	619.13	0.20
4 with last layer= 3.5 mm	5.00	2.50	0.50	545.80	69.00	835.31	0.20

Joint No.8 | Layers in order = FR4(1.6mm)+Al6061-T6(2.5mm) | Total Length=4.1 mm | M3							
Configuration	Total Length (mm)	L (mm)	n	Kb (kN/mm)	Ej (kN/mm^2)	Kj (kN/mm)	n*phi
3	4.10	2.85	0.50	478.78	22.84	214.44	0.35
3 with last layer= 3.5 mm	5.10	3.35	0.50	407.32	26.85	238.54	0.32

If the values of n,ϕ are known then we can calculate the values of $\Delta P_b/P_{et}$ which gives the fraction of the external force which is getting applied on the bolt. This value is considered reasonable if it is less than 0.2.
As seen from the above given tables, it can be seen that in many cases values of $n * \phi$ are higher than 0.2. Although, the external force is not known and the margin of safety is not fully calculated, efforts can be made to reduce the value of n*phi to at least less than 0.2. Therefore, some design changes can be implemented such as change in diameter or the length of the joint by adding a stub.

Future Subtasks :-

1. Learning more about doing random simulations on prestressed models using additional features of Ansys such as load combination or design assessment.
2. Prediction of equivalent static loads for dynamic loads.
3. Analysing response PSD from a random simulation.

4.7.3 Peripherals

Stand, Handle and Transportation box

Importance

Stand :- The stand helps in providing stability to the satellite in the process of integration.

Handle :- The handle helps in transferring the satellite from stand to the transport box. It enables us to carry it without touching it on the surfaces of the satellite.

Transport box :- Transport box helps us to safely carry the satellite for long distances. It will make sure that the satellite doesn't encounter any high loads during the transportation process.

Process

The video of the whole process of taking the satellite from the stand to putting it inside a transport box can be seen here.

1. The satellite is integrated on the stand. The satellite and the stand are connected by

M6 screws.

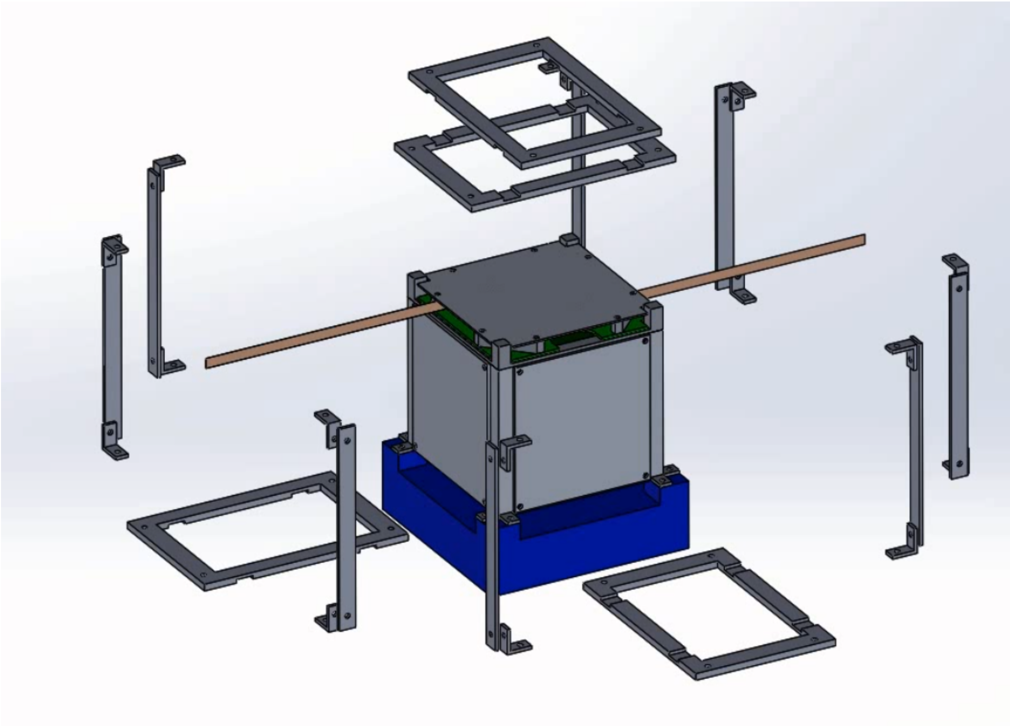


Figure 4.32: Sanket connected to the stand

2. After the integration process is completed, the satellite is to be transferred from the stand to the transport box to carry it from one place to another. So, handle is used here to do this. The handle is attached to the satellite as shown below.

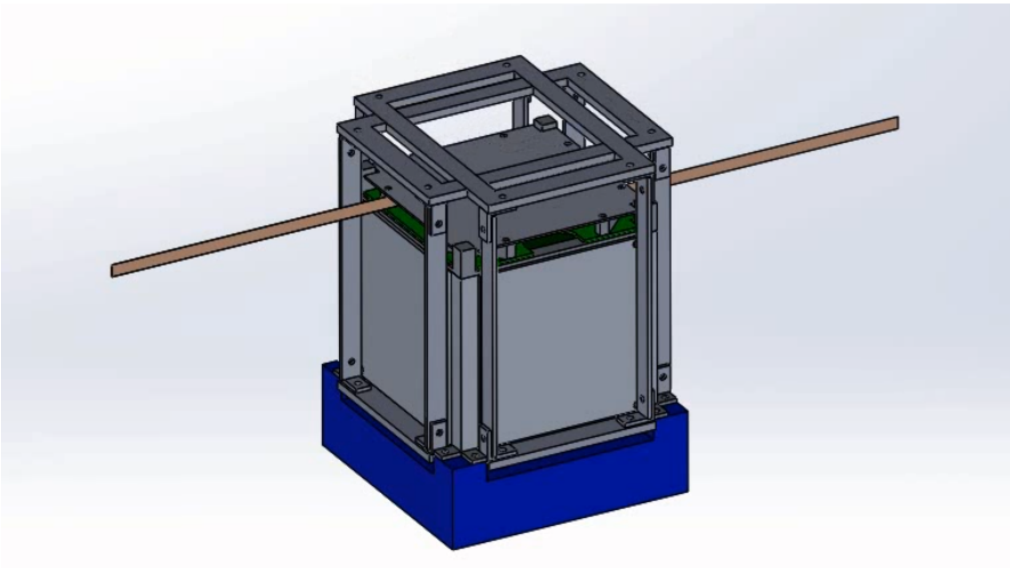


Figure 4.33: Sanket connected to handle and stand

3. Then, the satellite is detached from the stand and then inserted into the transport box.

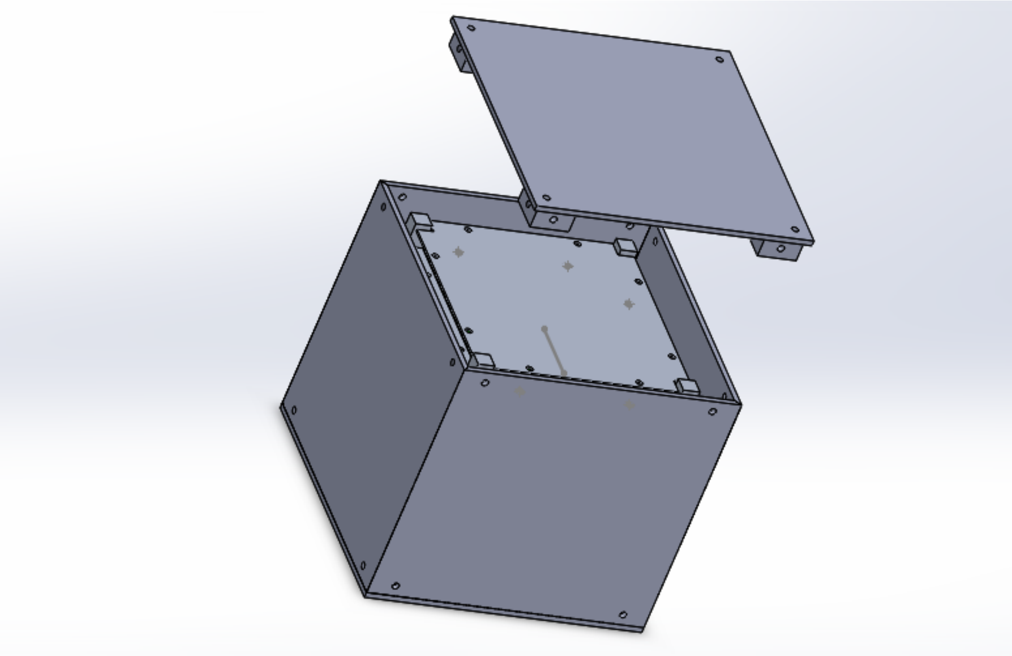


Figure 4.34: Sanket inside the transport box

Further Concerns :-

1. Vibration dissipation or damping using foam.
2. Reviewing the position and length of the screws to check for interference.
3. Reducing the complexity of the model to make it easier to manufacture.
4. Taking measures to stop the accumulation of static charge on the transport box.

4.7.4 Integration Sequence

Integration Sequence of Antenna Deployment System

Step No.	Step Description	Interface ID
1	The rods are attached to the fixture. The position of the rods is such that they will pass through the holes in the PCB that are made for the linear stubs.	
2	The PCB is placed on the fixture by carefully passing the holes for linear stubs present on the PCB through the rods attached on the fixture.	
3	The adhesive, Araldite AV138/ HV998, is applied to a linear stub and this stub is then fixed to the PCB by passing the holes in the linear stub through the rods on the fixture. This ensures that the holes of the linear stubs perfectly coincide with the holes on the PCB. Repeat this for the other three linear stubs.	69 71 73 75
4	After a few hours, the PCB is then taken out of the fixture, and is then left undisturbed for 2 days to let the adhesive to cure.	
5	The rods are detached from the fixture.	
6	The PCB, now with the linear stubs fixed on it, is again placed on the fixture.	
7	The PCB is fixed to the base of the fixture by using screws and washers made of acrylic, that combinely joins linear stubs, PCB and the base of the fixture.	69 71 73 75
8	The C-shaped subchassis and the interface blocks are attached to the PCB with the help of screws.	54 56
9	The detection switches are fixed to the PCB with screws.	84
10	The rail that will aid in the coiling of antennas is set up.	
11	Nylon thread is attached to one of the PVC films.	62
12	A marking is made on the nylon wire at the point where it is to be attached to the other PVC film.	
13	One part of the antenna is screwed to the interface block along with the PVC film which has nylon wire attached to it. The same is done for the other antenna.	55 57
14	The other part of the antenna is then screwed to the other interface block along with the PVC film.	55 57
15	The pipe which is to be used to coil the antennas, is placed on the rail.	
16	The other end of the antenna is attached to the pipe with a clip.	
17	The antenna is coiled by the combined rotational and translational motion of the pipe with the help of the clip attached.	

Step No.	Step Description	Interface ID
1	8 extruded stubs on the side rails are attached to the claw with the help of screws.	
2	Communication PCB is placed on the 4 support rails stubs and screwed	28 32 36 40
3	Claw is rotated by 180 degree and fixed at that position	
4	Electrical PCB is placed to the 4 support rails stubs and screwed.	27 31 35 39
5	Lower chassis is placed on top of the support rails and screwed.	30 34 38 42
6	System is rotated by 180 degree and fixed at that position	
7	Upper chassis is placed on top	29 33 37 41
8	ADS module is placed the upper chassis and fixed with the help of screws passing through the linear stub	69 71 73 75
9	Cover panel is placed on top of the ADS module and is screwed	68 70 72 74
10	Connector on the electrical PCB is connect to the one on Communication PCB through wires which are routed along the pcb and support rails as shown in the figure	22 23 24 25 26
11	Connector on the communication PCB is connect to the one on ADS module through wires which are routed along the pcb and support rails as shown in the figure	92 93
12	The entire system is placed on a stand where the side panels would be integrated.	43-50

18	The coiled antenna is then temporarily attached to C-subchassis with the help of a separate clip, and the pipe like structure is then removed.	53
19	The other antenna is also similarly coiled and attached to the corresponding C-shaped subchassis with a clip.	53
20	The nylon wire is then routed through the extruded stubs on the PCB , and is then passed through the nichrome wire.	63 64
21	The nylon wire is tied to the other PVC sheet such that the marked point coincides with the hole in the PVC sheet. The excess wire is cut off.	62

Integration Sequence of Sanket

4.8 Quality Assurance

4.8.1 Modelling and Simulation

Nomenclature of a complete CAD model has a fixed format of AAANNNXXXX where AAA= ADS for assembly of ADS, SAN for assembly of Sanket, AUX for Auxiliary system and BTP for Bolt Preload.
The format for simulation is AAANNNXXXX_MM where MM is the number of iterations of the simulation for the model AAANNNXXXX.

4.8.2 Manufacturing

Nomenclature of the complete prototype has a fixed format of AAAPXX where AAA= ADS for assembly of ADS, SAN for assembly of Sanket, P stands for prototype and XX stands for the number for iteration.
Manufacturing QA for the whole structure and individual part that will be used in on-board and testing is in the process of development.

4.8.3 Integration

Nomenclature of a complete CAD of ADS and Sanket have a fixed format of AAANNNXXXX where AAA= ADS for assembly of ADS and SAN for assembly of Sanket. The integration sequence is named with the assembly name followed by the sequence iteration like AAANNNXXXX_MM where MM is the version of integration sequence on the AAANNNXXXX CAD assembly.
Spreadsheets are maintained for documenting detailed integration sequences of ADS and Sanket. The sheet also contains the name of the creator, comments and decisions taken on that particular integration sequence.

Softwares Used

The team uses various softwares at different courses of the project. The softwares range from Simulation, CAD to coding platforms like MATLAB. Following is a table of various softwares used.

Softwares	**Use**
SolidWorks	Modeling of the Satellite Model
Spenvis	Radiation Shielding Simulation
Eagle CAD	Modeling of the PCBs
Ansys	Structural and Thermal Analysis of the Satellite
HFSS(Ansys) 13	Antenna Characteristics Simulation
LTspice	Electrical Simulation
Proteus	Electrical Simulation
MATLAB	Numerical Analysis

Table 17: List of Softwares used

Sanket System Members

Name	Sub-System	Area of Work
Karan Jagdale	Communication	Systems Engineer*
Mrigi Munjal	Mechanical	Structural Designing
Prashant Kurrey	Electrical	PCB Designing, Interfacing & Testing
Ashay Wakode	Mechanical	Structural Designing & Manufacturing
Pushkar Lohiya	Mechanical	Structural Designing & Simulation
Puneet Shrivas	Communication	FMECA
Anmol Sikka		Project Manager (2018-20)
Aniruddha Ranade		Project Manager (2018-20)
Sanskriti Bhansali	GNC	Project Manager*
Abhishek Kejriwal	Electrical	PCB Designing
Amrutha Lakshmi Vadladi	Electrical	Interfacing
Hemant Dilip Gidewar	Electrical	PCB Designing & Testing
Ritul Shinde	Mechnical	Structural Designing, Simulations & Integration
Hrithik Agarwal	Communication	PCB & Programming
Mohit Dhaka	Mechnical	Structural Designing, Simulations & Integration
Pranav G Kasat	Mechnical	Structural and Thermal Simulations
Shreya Laddha	Communication	PCB & Programming
Akshat Mehta	Electrical	PCB Designing
Ankit Kumar	Mechnical	Structural Designing & Manufacturing
Dhanush S	Mechnical	Bolt-Preload, Integration & Transportation
Ishan Phansalkar	Communication	Programming
Jayant Saboo	Mechnical	Thermal Simulations
Kriti Verma	Electrical	PCB Designing
Adesh Yadav	Communication	PCB Designing & Antenna testing
Leena Chaudhari	Mechnical	Structural Simulations & Integration
Navjit Debnath	Mechnical	Radiation Shielding
Shreeya Shrikant Athaley	Mechanical	Thermal Simulations
Shreyas Sabnis	Communication	PCB Designing
Vidushi Verma	Mechnical	Structural Design, Simulation & Integration
Vineet Gala	Communication	Antenna Simulation & Testing
Yatin Jindal	Electrical	PCB Designing

Table 18: List of System Members

* as of September 2020