



# Mechanical and Thermal Studies of IGOSat

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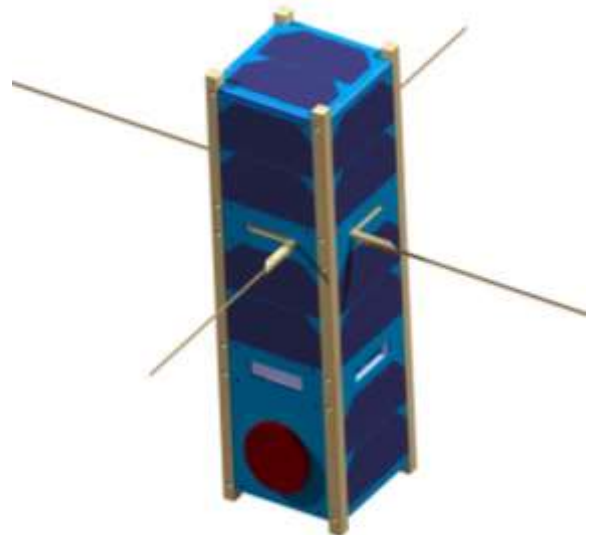
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Above all, I would like to express gratitude to my parents for allowing me to pursue my dreams and opt for such an incredible opportunity.

## **ABSTRACT:**

*This report presents the detailed study, method of analysis of the Thermal Model of the IGOSat in the Thermica Software by Thermal Control System. The main objective is to obtain the thermal behavior of the components in the Space Environment by obtaining their temperature ranges. It also explains the assumptions made as well as the problems faced in obtaining the results to input into the simulations. At the end of the report, the results of sensitivity analysis helps us to know which parameters affect the temperatures of the components the most. And another reason that the insufficient data for few components exists made the necessity to perform the sensitivity analysis. From the results, it can be concluded that conduction has major effect on temperature variation of components rather than optical properties, thermal conductivity of PCB, spin rate.*

## **ABBREVIATIONS:**

CNES - Centre National d'Etudes Spaciales (National Centre for Space Studies)

ACS - Attitude Control System

GPS - Global Positioning System

STM - Structural and Thermal Model

MPCC - Multi-Pixel Photon Counter

SiPM - Silicon Photo Multiplier

CeBr<sub>3</sub> – Cerium Bromide

EPS – Electric Power Supply

PCB – Printed Circuit Board

## **1. INTRODUCTION:**

IGOSat (Ionospheric Gamma Ray Observation Satellite) is a CubeSat project of the laboratory of excellence (Labex) UnivEarthS, carried out at University Paris Diderot set up with the local support of the laboratories APC (AstroParticule and Cosmologie) and IPGP (Institute de Physique du Globe de Paris). IGOSat project is in collaboration with the CNES (French Space Agency).

### **1.1 ABOUT THE MISSION:**

The project instigated in September 2012 and IGOSat will be launched during the period 2017-2018 which is a 3Unit CubeSat with 2 payloads: a GPS map and a Scintillator. The main objective of this mission IGOSat is to study the electronic content present in the Ionosphere.

IGOSat has entered the phase C after finishing the review on June 8<sup>th</sup> 2016. Since the Satellite has come to Phase C where the design and the components of various subsystems have been finalized there is necessity to perform the Thermal Analysis so that the Satellite meets the Thermal requirements.

The Satellite consists of several subsystems:

1. PAYLOAD consists of GPS and Scintillator Subsystem
2. PLATFORM consists of Structure, Computer, ACS, Power, Communications Subsystems

For all the above subsystems there is a necessity to analyze their Thermal behavior in the Space Environment since electronics dissipate heat while working and their operation conditions vary with respect to Temperature.

## **2. DESIGN AND OBJECTIVE:**

The Thermal Control System is very important to make the mission successful. So the design has to be made very carefully keeping all the extremities in mind and also including the margins to make sure the components do not fail during launch or in it's the orbit.

The main objective of the Thermal Control Subsystem is to make sure that during the complete mission of the Satellite all the components work well irrespective of the extremities faced in the Space Environment. It must also ensure that the components will stay in their survival temperature limits during the entire mission.

The TC system should design and simulate the space environment. It should take the orbital parameters into account and estimate the temperature extremities reached by the components.

Later this should be confirmed with the help of rigorous Mechanical and Thermal tests before launch.

## **2.1 PREVIOUS WORK:**

Previously preliminary Thermal analysis was performed for the Satellite in Systema plugin Thermica Software. At that time the Satellite design was not finalized and the satellite was in Phase A which implies many parameters were not confirmed. Many assumptions about the Orbital Parameters, Material Properties of the Satellite's Components were made and the analysis was performed. But this analysis was a head start for the Thermal System to proceed with the analysis in the Thermica Software.

## **2.2 MOTIVATION OF THE PROJECT:**

With respect to time within these two years various designs have been implemented on the Structure and different components have been chosen by different subsystems. Also varied choices have been made in material selection which is very important from the Thermal point of view. The choices have been made based on the material's Mechanical as well as Thermal properties which are very important. Since the chosen materials were not available compromise has been made with the materials having similar properties. So there is a necessity to perform the analysis to confirm that the materials chosen fulfill our requirements.

## **3. HIGH DEFINITION IMAGES FOR POSTER:**

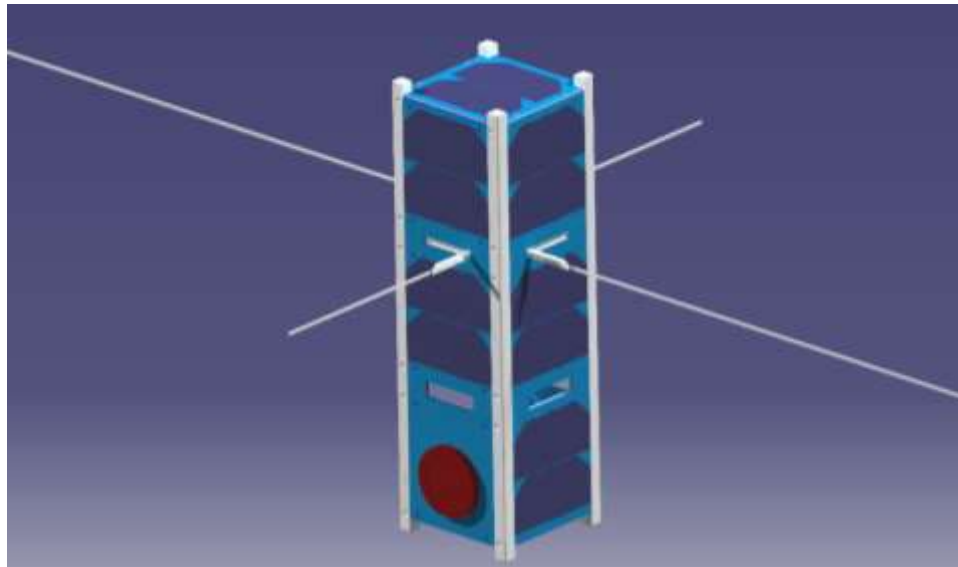
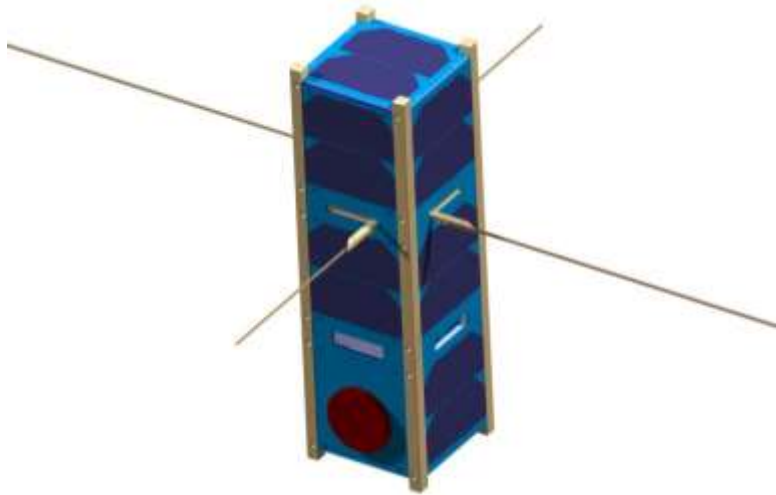


Fig – 1: Rendered image of IGOSat in Catia

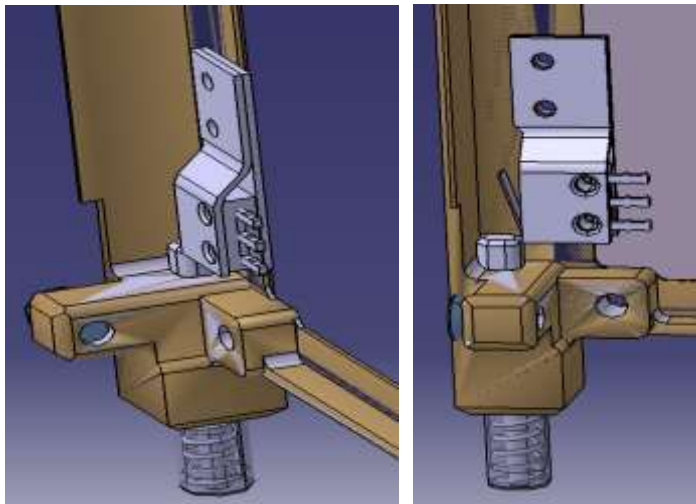


**Fig – 2: High Definition image of IGOSat for the Poster**

The above is the image of the IGOSat which was made for the poster. The HD image was rendered in CATIA after the final integration of the Solar cells on to the Panels and the Solar Panels into the Structure.

#### **4. NEED FOR THE NEW KILL SWITCH INTEGRATION MECHANISM:**

Previously kill switch was modelled into the Structure rails with the spring mechanism. Since the Structure has been modified this year as well as the integration of Side Frame with the ribs to the Structure the previous mechanism would not be practically possible to integrate kill switch. Also new kill switch was chosen with different dimensions. So a new kill switch mechanism has to be designed.



**Fig-3 & 4 Old mechanism of Kill Switch**



## **4.1 INTEGRATION OF KILL SWITCH:**

The Kill Switch is the most important component for the Satellite because there should be no electrical mishap before launching into the Space Environment when the Satellite is inside the Pod (Deployer). The Kill Switch has been integrated into the Satellite with a new mechanism. The location of the Kill Switch should be in such a way that when it engages with the structure there will be no electrical connection. So this is the main function of the Kill Switch.

A new side frame has been designed in CATIA, manufactured using 3D printing to make sure that the design will work when integrated into the Satellite and has been finalized. Then the side frame drawings have been finalized and have been sent to manufacturing. The procedure about the idea of integration and the modifications has been explained in detail below.

## **4.2 PROCEDURE AND PROBABLE WAYS FOR THE INTEGRATION:**

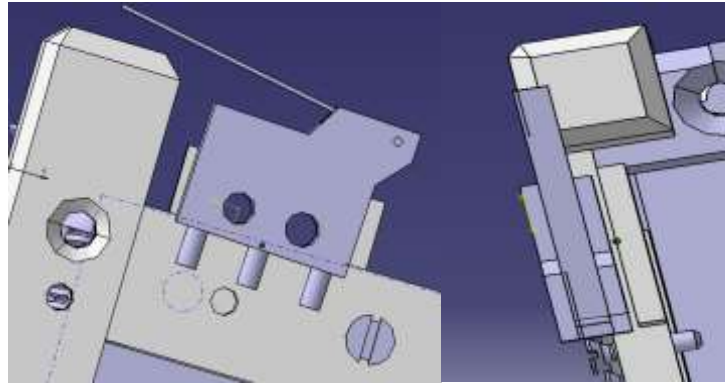
### **1. Location - Problems with outside the panel**

- Should make pocket for the side as well as bottom panel.
- Wiring would be problematic although thickness of switch is just 5.1mm since there will be Solar cell as well as Panel located.
- In CubeSat acceptance checklist the dimensions on the sides of the structure should not exceed 6.5mm.



**Fig – 5: New Kill Switch**

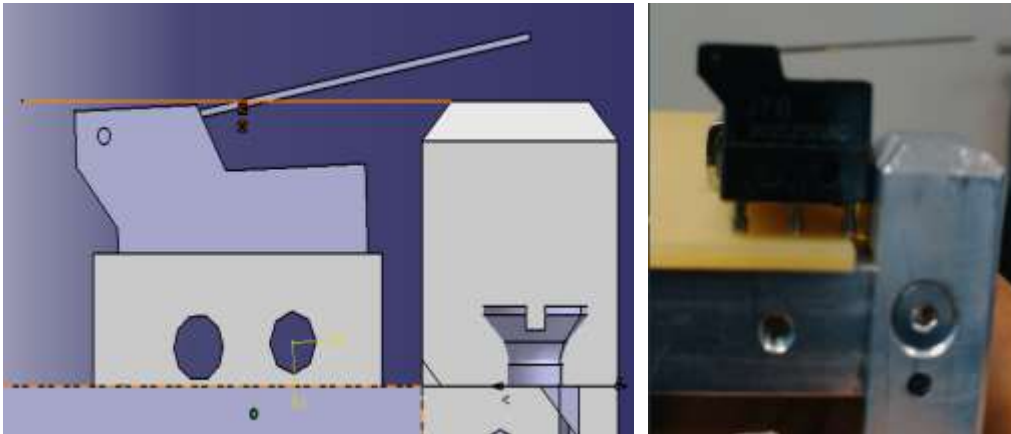




**Fig – 6 & 7 : Integrated New Kill Switch**

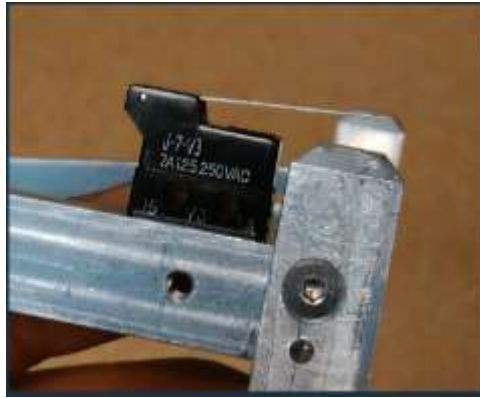
## 2. Location - Problems with inside the panel (bottom)

- should make a pocket in the bottom panel of kill switch size
- should extrude on sideframe to screw the killswitch
- If we place it in this manner the hinge height is greater than the rail's bottom edge so



**Fig – 8 : New Kill Switch position**

- If the pod has a plane surface hinge will touch the surface first but the lever does not get engaged with the Structure.
- Solution for this is to give an inclined slot on the surface of the sideframe
- If the pod has surface at the corners then the lever gets engaged the below solution is preferred.



**Fig – 9: Problem with the height of the new Kill Switch**

#### **4.3 3D PRINTED KILL SWITCH:**



**Fig – 10: 3 -D Printed new Sideframe**

The above image is the 3D Printed Kill Switch Side Frame to make sure the idea will integrate the Kill Switch into the Structure without any problems. And basing on this the decision was taken to proceed for manufacturing the SideFrame with Aluminium 2017.

#### **4.4 KILL SWITCH SIDE FRAME:**



**Fig – 11: Manufactured new Sideframe**



**Fig – 12: Kill Switch Assembly Back View**



**Fig – 13: Kill Switch Assembly Front View**

The above images clearly show the extruded part on the sideframe for mounting the Kill Switch. And it is clearly visible that an inclined draft has been provided to solve the problems mentioned above.

## **5. SPACE ENVIRONMENT:**

As we know that there are basically 3 modes of heat transfer:

1. Conduction
2. Convention
3. Radiation

Out of the above 3 modes, Conduction and radiation are will be experienced by the Satellite in the Space Environment. Since there is no medium like air or any fluid for either Natural or Forced Convection the heat transfer by this mode is neglected.

In Space the Satellite receives different radiations. They are explained as follows:

1. The Radiation from Sun: The Satellite receives direct radiation from Sun which consists majorly of Ultraviolet radiation. The maximum value of this Solar Flux is  $1414\text{W/m}^2$ . But since this value varies with respect to the orbit inclination angle as well as the location of

the Satellite in the orbit the mean value of the flux considered for computation is  $1376\text{W/m}^2$ .

2. Infra-Red Radiation from Earth: The Earth absorbs the IR radiation and emits the same. The average value of this flux is  $237\text{W/m}^2$ .
3. Albedo radiation: The Earth receives the radiation from the Sun and also emits the same. This radiation is known as the Albedo Radiation. It varies with respect to the density of the atmosphere since there will be polar caps, clouds as well as forest area which absorb and emit the radiation differently. So on an average the albedo co-efficient is taken as 0.3.

## **6. THERMAL CONTROL SYSTEM REQUIREMENTS:**

QB50-SYS-1.6.1 The CubeSat shall maintain all its electronic components within its operating temperature range while in operation and within survival temperature range at all other times after deployment.

QB50-SYS-1.6.2 The CubeSat shall survive within the temperature range of  $-20^{\circ}\text{C}$  to  $+50^{\circ}\text{C}$  from the time of launch until its end of life.

Recommendation 16: Due to the lessons learned from the QB50 precursor campaign, it is recommended for all QB50 CubeSats to have a battery heater.

Since we follow the QB50 requirements the above requirements should be met by the Satellite at all times when in the Space Environment.

### **6.1 THERMAL TESTING REQUIREMENTS FOR LAUNCH:**

1. THERMAL VACCUM TEST: This test needs to be done on the Satellite as it provides the realistic space environment. With the help of this test we can understand the behavior of components in vaccum.

2. THERMAL CYCLING TEST: This is to understand the stable behavior of the Satellite in the vaccum. So a cycle of same temperatures are given to the Satellite maintaining the Space Environment.

**6.2. IDENTIFYING THE TEMPERATURES OF COMPONENTS:** Before performing Thermal analysis, it's necessary to find out the most sensitive components by identifying their operating temperature range. Since the components should work throughout the mission period, the operating temperature ranges of the components are considered.

#### TOP CUBE:

1. Scintillator Assembly consists of MPCC/SiPM Array, BC-412 Plastic, CeBr3 Crystal as well as Aluminum Shielding.
2. EPS board
3. Four Batteries (18650 Li ion) with shielding mounted with Stainless Steel screws to the PCB.

#### MIDDLE CUBE:

1. Radio Card Assembly
2. On Board Computer
3. Attitude Control Board (Magnetorquers)
4. Empty PCB

#### BOTTOM CUBE:

1. GPS Receiver Card
2. GPS Antenna
3. Aluminum mass balancer
4. Earth Sensor

For the electrical connections between each subsystem PC 104 connector was used.

### 6.3 OPERATING TEMPERATURES OF COMPONENTS:

| S.NO | NAME OF THE COMPONENT   | MINIMUM OP. TEMPERATURE | MAXIMUM OP. TEMPERATURE |
|------|-------------------------|-------------------------|-------------------------|
| 1.   | SOLAR PANELS            | -40                     | 85                      |
| 2.   | PCB BOARD               | -40                     | 85                      |
| 3.   | GPS ANTENNA             | -40                     | 85                      |
| 4.   | GPS RECEIVER MODULE     | -40                     | 85                      |
| 5.   | UHF/VHF ANTENNA         | -20                     | 60                      |
| 6.   | EASIROC PCB             | -40                     | 85                      |
| 7.   | AMSAT PCB               | -20                     | 45                      |
| 8.   | ON BOARD COMPUTER BOARD | -25                     | 65                      |
| 9.   | SUN SENSOR              | -25                     | 50                      |
| 10.  | MAGNETORQUER BOARD      | -40                     | 70                      |
| 11.  | BATTERIES               | -20                     | 60                      |
| 12.  | MAGNETOMETER            | -40                     | 85                      |
| 13.  | SiPM                    | -20                     | 60                      |
| 14.  | PLASTIC (BC 412)        | -60                     | 60                      |
| 15.  | CeBr3 CRYSTAL           | -20                     | 60                      |

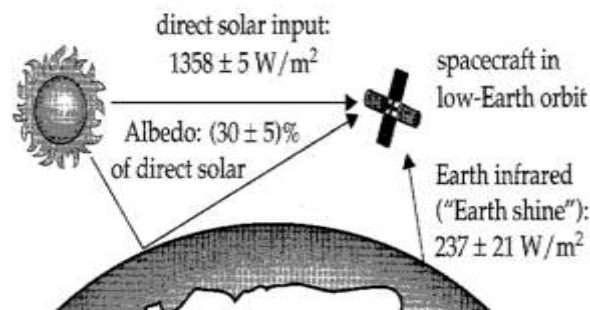
**Fig – 14: Operating Temperatures of Various Components**



From the above table, it's evident that batteries, UHF Antenna, Amsat Board, SiPM, CeBr3 crystal have low minimum operating temperatures. These components may get affected in the extreme conditions when the Satellite is in eclipse i.e in cold case. Whereas Amsat PCB is the most sensitive component for the hot case as well as for the cold case.

## 6.4 CALCULATION OF EXTREME TEMPERATURES:

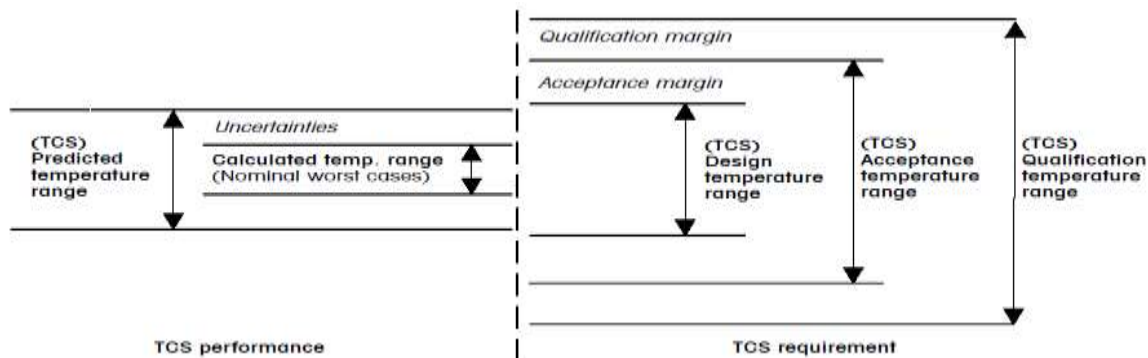
To have an estimation of the maximum temperatures reached by the Satellite when facing the direct sun as well as in eclipse, thermal balance equation is used. To apply the thermal balance equation firstly the radiations that affect the Satellite are to be listed out which are detailed. The Solar, Albedo as well as Infrared radiation emitted by Earth have been described above in the section "Space Environment". Later, by equating the below the temperatures for the steady state were obtained for the Satellite. ASSUMPTION: Assuming the Satellite is a black body to obtain the maximum temperature. But we know that pragmatically a Satellite cannot be a black body.



The above figure shows the radiation that is present in the space which affects the satellite. The following equation is used.

$$Q_{\text{absorbed}} - Q_{\text{emitted}} + Q_{\text{power-generated}} = 0$$

## 6.5 MARGINS:



**Fig – 15: Temperature definitions for thermal control system**

## 6.6 COMPONENTS AND THEIR PROPERTIES

| System      | Component                | Plane | Mass (kg) | Area (per side) (m <sup>2</sup> ) | Thickness (m) | Specific Heat Capacity (J/Kg K) | Mass Heat Capacity (J/K) | Thermal Conductivity (W/mK) |
|-------------|--------------------------|-------|-----------|-----------------------------------|---------------|---------------------------------|--------------------------|-----------------------------|
| GPS         | Antenna without PCB      | MB    | 0.072     | 0.002                             | 0.023         | 900                             | 64.8                     | 0.3                         |
|             | Receiver PCB             | DS    | 0.106     | 0.00864                           | 0.0016        | 900                             | 95.4                     |                             |
| COM         | Antenna                  | MB    | 0.098     | 0.009604                          | 0.0057        | 900                             | 88.2                     | 0.3                         |
|             | Radio card               | MB    | 0.192     | 0.00864                           | 0.0016        | 1800                            | 345.6                    | 1.5                         |
| SCI         | PCB                      |       | 0.026     | 0.00864                           | 0.0016        | 1200                            | 31.2                     | 0.3                         |
|             | SiPM                     | HIEN  | 0.0042    | 0.000169                          | 0.001365      | 900                             | 3.78                     | 0.3                         |
|             | Inner Crystal (CeBr3)    | DS    | 0.002     | 4.1E-05                           | 0.012         | 276.5                           | 0.69                     | 0.61                        |
|             | Easiroc Board            | MB    | 0.1       | 0.00864                           | 0.0016        | 1200                            | 120                      | 0.3                         |
|             | Outer Plastic(BC-412)    | OLD   | 0.0724    | 0.00029                           | 0.023         | 1500                            | 108.6                    | 0.3                         |
| OBC         | computer Board           | DS    | 0.05      | 0.00864                           | 0.0016        | 1200                            | 60                       |                             |
| ADCS        | Torquer Board            |       | 0.026     | 0.00864                           | 0.0016        | 900                             | 23.4                     | 0.3                         |
|             | Torquer 1                | MB    | 0.0268    | 6.36E-05                          | 0.058         | 300                             | 8.04                     |                             |
|             | Torquer 2                | MB    | 0.0268    | 6.36E-05                          | 0.058         | 300                             | 8.04                     |                             |
|             | Torquer 3                | MB    | 0.0268    | 0.001422                          | 0.014         | 300                             | 8.04                     |                             |
|             | Magnetometer             | old   | 0.015     | 0.0001                            | 0.005         | 900                             | 13.5                     | 314                         |
| POWER       | EPS Board                | MB    | 0.062     | 0.0086                            | 0.0016        | 900                             | 55.8                     | 0.3                         |
|             | Battery PCB              | MB    | 0.026     | 0.00864                           | 0.0016        | 600                             | 23.4000                  | 0.3                         |
|             | Battery Cell (each)      | DS    | 0.039     | 0.000254                          | 0.064         | 940                             | 36.6600                  | 0.2                         |
| SOLAR CELLS | Bottom cube              | MB    | 0.008     | 0.00803                           | 0.0016        | 350                             | 2.8000                   | 46                          |
|             |                          | MB    |           |                                   |               |                                 |                          |                             |
|             | Middle cube              | MB    |           |                                   |               |                                 |                          |                             |
|             |                          | MB    |           |                                   |               |                                 |                          |                             |
|             | Top cube                 | MB    |           |                                   |               |                                 |                          |                             |
|             |                          | MB    |           |                                   |               |                                 |                          |                             |
|             | Top side                 | MB    |           |                                   |               |                                 |                          |                             |
|             | Bottom side              | MB    |           |                                   |               |                                 |                          |                             |
| PANELS      | 1 panel for 1U Cube mass | MB    | 0.0316    | 0.00865                           | 0.0016        | 1200                            | 38.0040                  | 0.3                         |
| EMPTY       | Empty Board              | MB    | 0.026     | 0.00865                           | 0.0016        | 1200                            | 31.2000                  | 0.3                         |
|             | Mass balancer            | MB    | 0.202     | 0.00865                           | 0.01          | 880                             | 177.7600                 | 134                         |

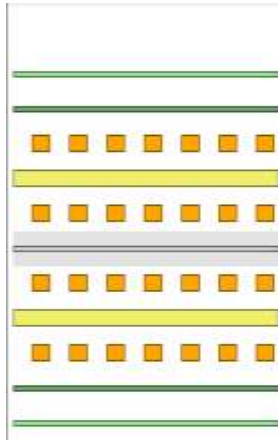
From the above table, the thermal capacitance is input into Thermica software with the help of user input file.



## 6.7 PROBLEMS IN CALCULATIONS:

1. Thermal Conductivity of PCB
2. Complex Subsystem Material Data

### 1. THERMAL CONDUCTIVITY OF PCB - PROBLEM:



| Layer Name     | Type                 | Material         | Thickness (mm) | Dielectric Material | Dielectric Constant | Pullback (mm) | Orientation |
|----------------|----------------------|------------------|----------------|---------------------|---------------------|---------------|-------------|
| Top Overlay    | Overlay              |                  |                |                     |                     |               |             |
| Top Solder     | Solder Mask/Coverlay | Surface Material | 0.01016        | Solder Resist       | 3.5                 |               |             |
| L1             | Signal               | Copper           | 0.03536        |                     |                     |               | Top         |
| Dielectric 1   | Dielectric           | Core             | 0.254          | FR-4                | 4.2                 |               |             |
| L2             | Signal               | Copper           | 0.036          |                     |                     |               | Not Allowed |
| Dielectric 3   | Dielectric           | Prepreg          | 0.127          |                     | 4.2                 |               |             |
| L3             | Signal               | Copper           | 0.036          |                     |                     |               | Not Allowed |
| Dielectric 2   | Dielectric           | Core             | 0.254          |                     | 4.2                 |               |             |
| L4             | Signal               | Copper           | 0.03536        |                     |                     |               | Bottom      |
| Bottom Solder  | Solder Mask/Coverlay | Surface Material | 0.01016        | Solder Resist       | 3.5                 |               |             |
| Bottom Overlay | Overlay              |                  |                |                     |                     |               |             |

The above figure is having the blocks of copper (orange) in the PCB designed in a software by the Electronics Engineer. Our PCB design is that it is FR4 which is Flame retardant consisting of Copper layers thickness 75 micro metres of 4 layers to increase the conduction. Since in the above figure as it's clearly obvious that the copper layers are not continuous it's difficult to calculate the effective thermal conductivity.

The thermal conductivity values of PCB (1.6mm thick in total) is 0.23W/m-K

Specific Heat Capacity= 1200J/kg-K

Density = 1900kg/m<sup>3</sup>

Taking copper thermal conductivity value as K = 380 W/m-K

To find the effective conductivity of PCB along the board which will be increased due to the copper layers of thickness 75 micro meters of 4 layers

For K<sub>xy</sub>(in plane) below formula was used and calculated. For this the K<sub>eff</sub> obtained was 71.43W/m-K (assuming copper layers are as same dimensions of PCB and is continuous).And for finding for K<sub>z</sub>(through plane) I get the K<sub>z</sub> eff = 0.28 by following the below formula.

$$K_{Through} = \frac{\sum_{i=1}^N t_i}{\sum_{i=1}^N t_i / \kappa_i}$$

$$K_{In-plane} = \frac{\sum_{i=1}^N \kappa_i t_i}{\sum_{i=1}^N t_i}$$

Since PCB is anisotropic if it is considered as a single node in Thermica then there will be uniform temperature throughout the node. But if the non-uniformity of temperature is required then each side of the PCB is to be considered as a single node, for this it should be modeled as a 3D object, and plane as well as through conductivities are to be mentioned.

## **6.8 COMPLEX SUBSYSTEM MATERIAL DATA:**

Since the subsystems like ON BOARD COMPUTER, RADIO CARD, UHF ANTENNA has more electronic components and it is difficult to obtain the material of each component. So they can be modelled as a simple PCB with more thickness (2D rectangle with thickness overloaded in Thermica). For density of unknown subsystems since I have the volume and mass of the components I have calculated the density and input that value. But if the Thermal Capacitance is specified in the user input file then the Specific Heat Capacity value as well as density is not required to be specified in Thermica Module because if done then the user input values will not be considered.

## **6.9 SOLUTIONS FOR THE ABOVE PROBLEMS:**

For the PCB problem a sensitivity analysis has been performed on the suggestion of the CNES Thermal Engineer for different thermal conductivities. With the help of the Sensitivity analysis results the final value for the thermal conductivity of the PCB was decided.

For the second problem, the subsystems were modelled as a PCB with higher thickness but considered as a single node and given their internal dissipation. So a uniform temperature will be recorded and the best way to validate this results for different subsystems is to perform the thermal tests.

## **7. PROCEDURE OF THERMAL ANALYSIS IN THERMICA:**

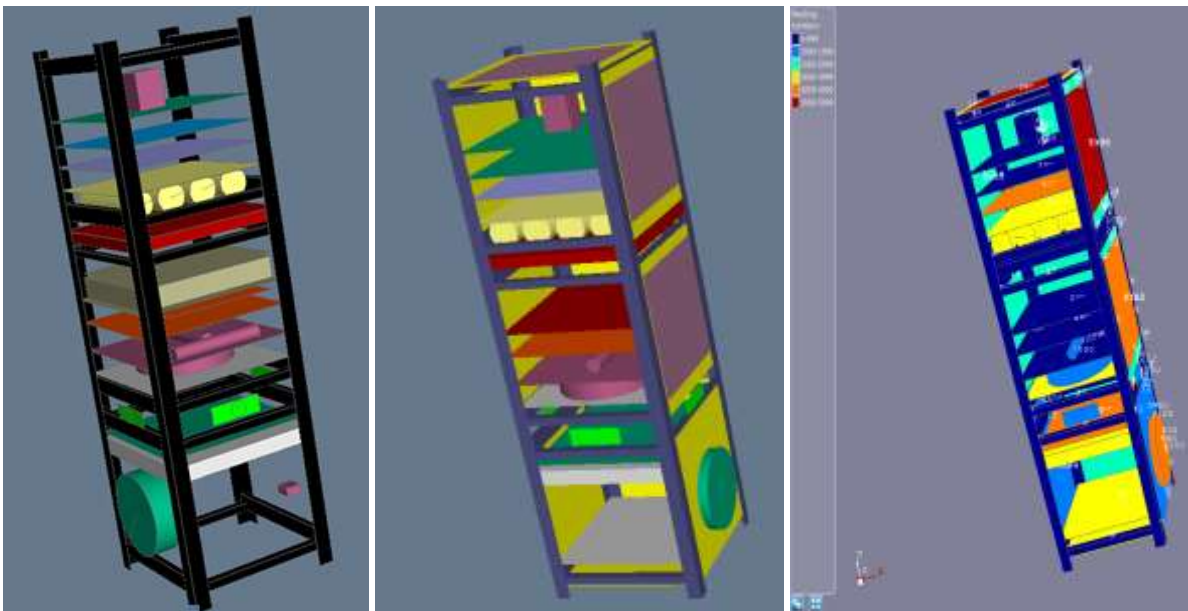
- a. Geometrical Modelling
- b. Meshing And Material Properties
- c. Trajectory
- d. Kinematics
- e. Mission
- f. Processing
- g. Calculation And User Input
- h. Thermica Solver

### **a. Geometrical Modelling:**

In Thermica, a simple model was built which resembles the IGOSat. To reduce the complexities each subsystem was modelled as a single node. Volume elements are not created since they are used to calculate the non-uniformities in Temperature of a component.

### **b. Meshing and Material Properties:**

After modelling each component their optical properties like emissivity and absorptivity were input accordingly. Thermal Conductivity also was given in the Thermica properties tab.



**Fig – 16: Model of IGOSat in Thermica**

### **c. Trajectory:**

The below image is the screenshot of the Trajectory tab in Thermica Software. This feature is a huge advantage in Thermica Software since we can input the orbit parameters which will create more realistic simulation environment.

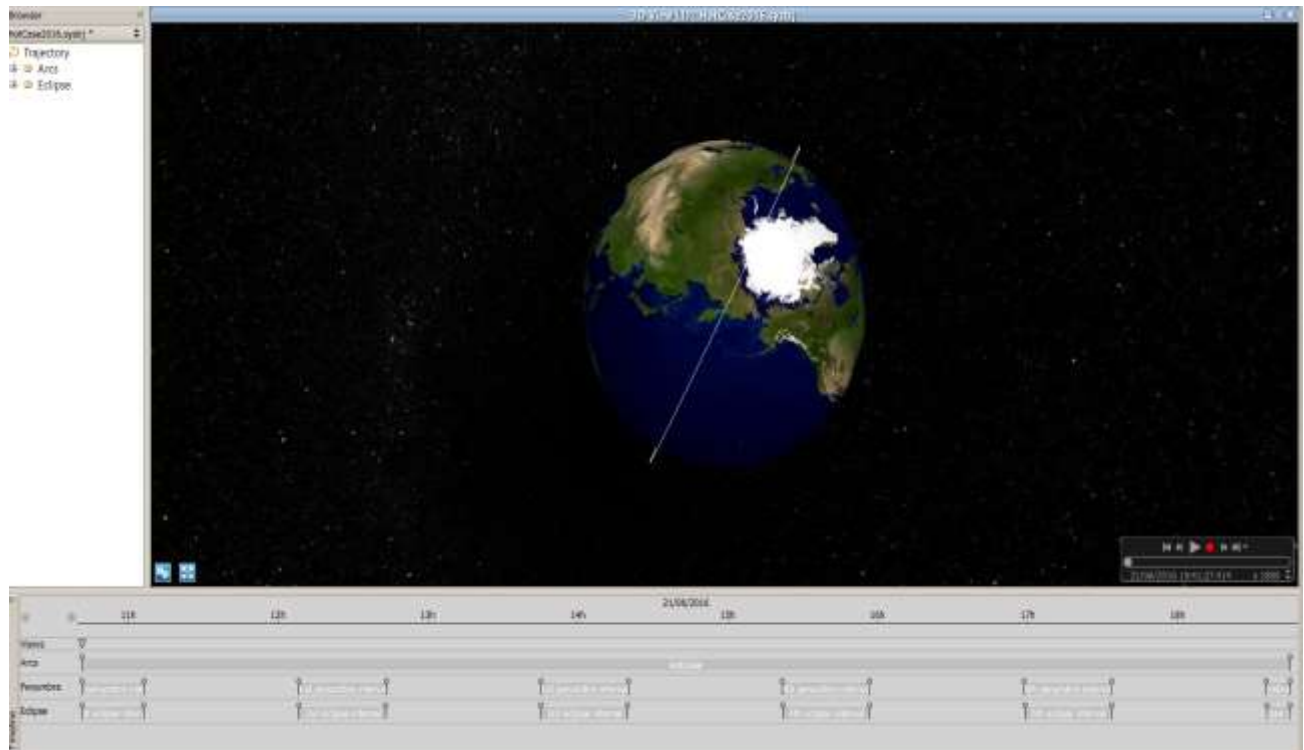
The input orbit parameters are as follows:

Type of Orbit: Sun Synchronous

Altitude: 600 Kilo meters

No. of Revolutions: 5

Reference Date: Winter Solstice (Hot Case) and Summer Solstice (Cold Case)



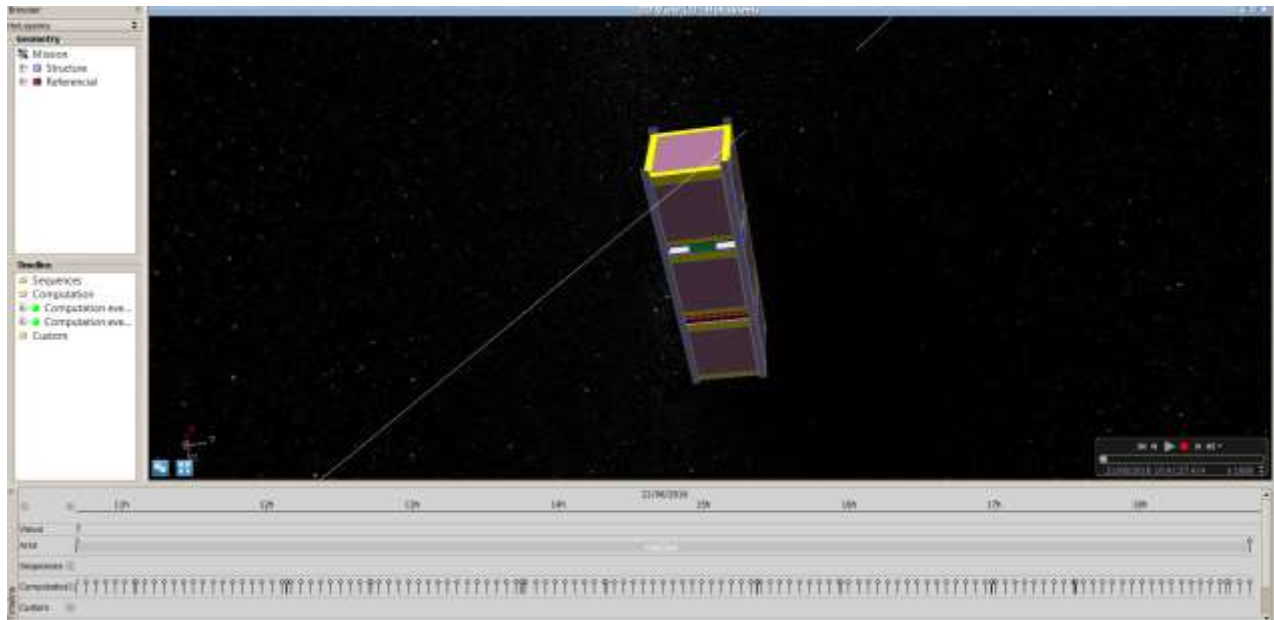
**Fig – 17: Trajectory in Thermica**

#### **d. Kinematics:**

In this tab of Thermica Software, the orientation of Satellite in the orbit was given with the help of pointing vectors. The pointing vectors were given for Orbit Planet reference as well as the Orbit Velocity Vector were given. The orientation of the Satellite with respect to the Orbit Planet Reference is given as  $(X, Y, Z) = (0, 0, -1)$ . The Orbital Velocity Vector of the Satellite was input as  $(X, Y, Z) = (1, 0, 0)$ .

#### **PARAMETERS OF ROTATION:**

The axis of the rotation of the Satellite is Z-axis which was input as  $(0, 0, 1)$ . The rotational speed was input as 10rev/hour. This parameter was varies with different values and the final analysis was done with 0.15rev/hour which was chosen to be the optimal value by the GPS team.



**Fig – 18: Trajectory in Thermica – Satellite in its Low Earth Orbit**

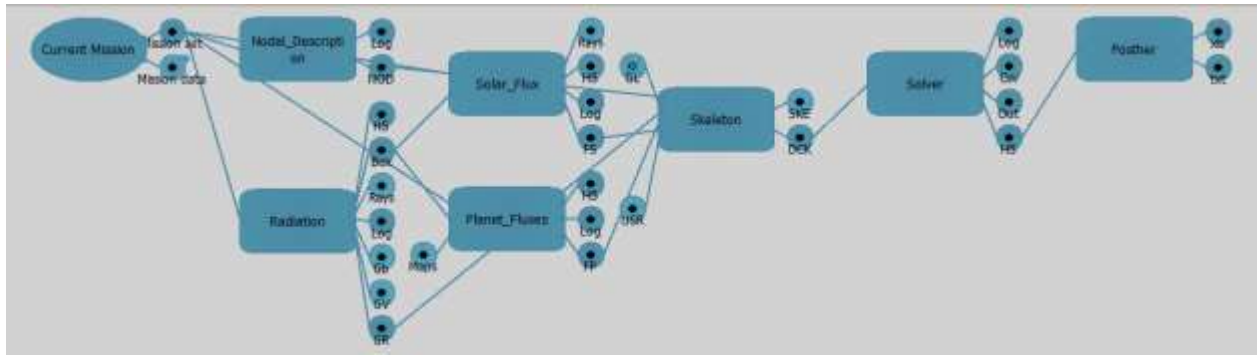
#### **e. Mission:**

The mission tab assembles the geometric model, trajectory and the kinematic model. All of the aforementioned models should be loaded into a new mission. Then the events were computed automatically at different positions in the trajectory by the software. After creating mission we can simulate and run the video and can view the way our Satellite orients itself and revolves around the Earth. This helps to crosscheck the parameters input in the above models.

#### **f. Processing:**

This tab of Thermica has pictorial representation of how all the sub-models connect with each other to give the final output of the simulation in required format by the user. The below image illustrates the way all the models are connected as mentioned above. Different components of Thermica were collected and formed as below. The Skeleton consists of our model which was described above till now. The Solar and Planetary fluxes were input into the Software. The final output was obtained in the form of excel sheet which contains the temperatures of different nodes at different positions in the orbit.





**Fig – 19: Processing Tab in Thermica**

**g. Calculation and User Input:** The conductive links which are to be input via User File into Thermica are to be calculated for every node. The Below image of excel sheet shows the calculations performed for the conductive links.

## 7.1 RESULTS:

**1. HOT CASE:** This is one of the extreme conditions experienced by the Satellite in its orbit. In this case, the Satellite operates in Mission mode which has the both the GPS and Scintillator as ON and hence the highest power consumption. In addition to the high power consumption, the margins of the power consumption have been included in this mode for all the subsystems so that the highest temperatures can be experienced by the Satellite. The margins in the power consumption are in correspondence with the acceptance margins mentioned above for the Thermal Control System. In this case when the Satellite directly faces the Sun the hottest temperature is recorded.

| Subsystem | Major Component | Margin (%) | Power Consumption (mW) |
|-----------|-----------------|------------|------------------------|
| GPS       | Antenna         | 20         | 350                    |
|           | RM Card         | 10         | 1350                   |
| SCI       | Easiroc Board   | 30         | 390                    |
| OBC       | Computer Board  | 20         | 480                    |
| TEL E     | Radio Card      | 30         | 6500                   |
|           | Antenna         | 10         | 30                     |
| AOCS      | Torquer Board   | 30         | 1300                   |
| POWER     | EPS             | 30         | 120                    |
|           | BATTERY         | 10         | 10.3                   |

**Fig – 20: Power consumption with margin (Mission Mode) for Hot case**

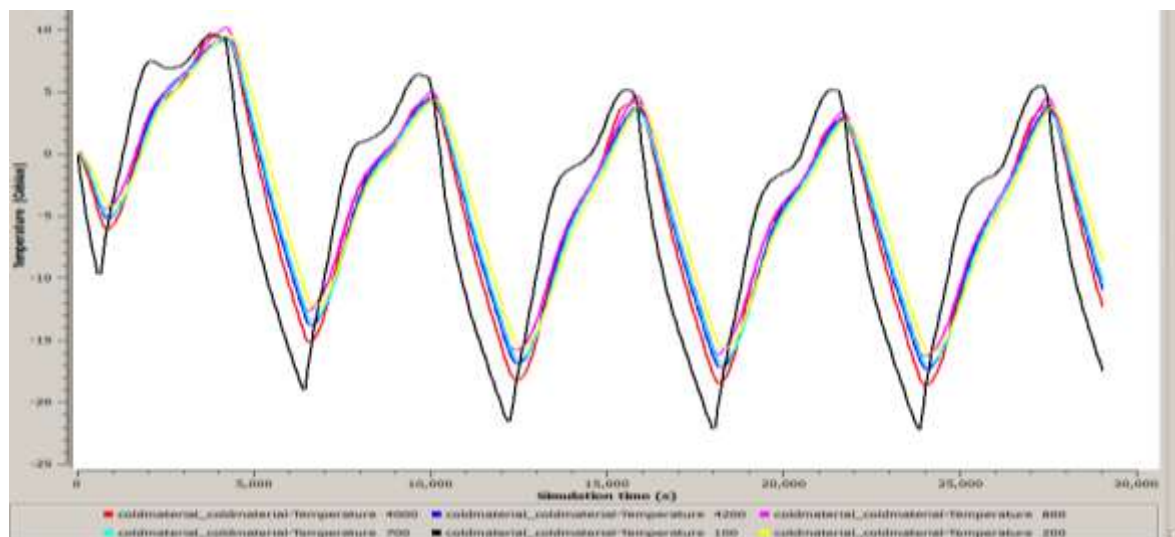
**COLD CASE:** This is another extreme case in which the Satellite experiences very cold conditions i.e least temperatures are recorded in this case. When the Satellite operates in its Survival mode this case is obtained. The worst case is obtained when the power consumption is exact without the margins unlike in hot case. The more margin we give for the power the hotter is the satellite which is not the extreme case. And in this cold case trajectory during the Eclipse interval for approximately 40minutes the lowest temperatures is recorded by various subsystems.

| Subsystem | Major Component | Margin (%) | Power Consumption (mW) |
|-----------|-----------------|------------|------------------------|
| GPS       | Antenna         | 20         | 0                      |
|           | RM Card         | 10         | 0                      |
| SCI       | Easiroc Board   | 30         | 0                      |
| OBC       | Computer Board  | 20         | 400                    |
| TEL E     | Radio Card      | 30         | 77.7                   |
|           | Antenna         | 10         | 30                     |
| AOCS      | Torquer Board   | 30         | 0                      |
| POWER     | EPS             | 30         | 96.1                   |
|           | BATTERY         | 10         | 10.3                   |

**Fig – 21: Power consumption without margin (Survive Mode) for Cold case**

In the above table, zero power consumption implies that the corresponding component is in OFF mode and hence the consumption.

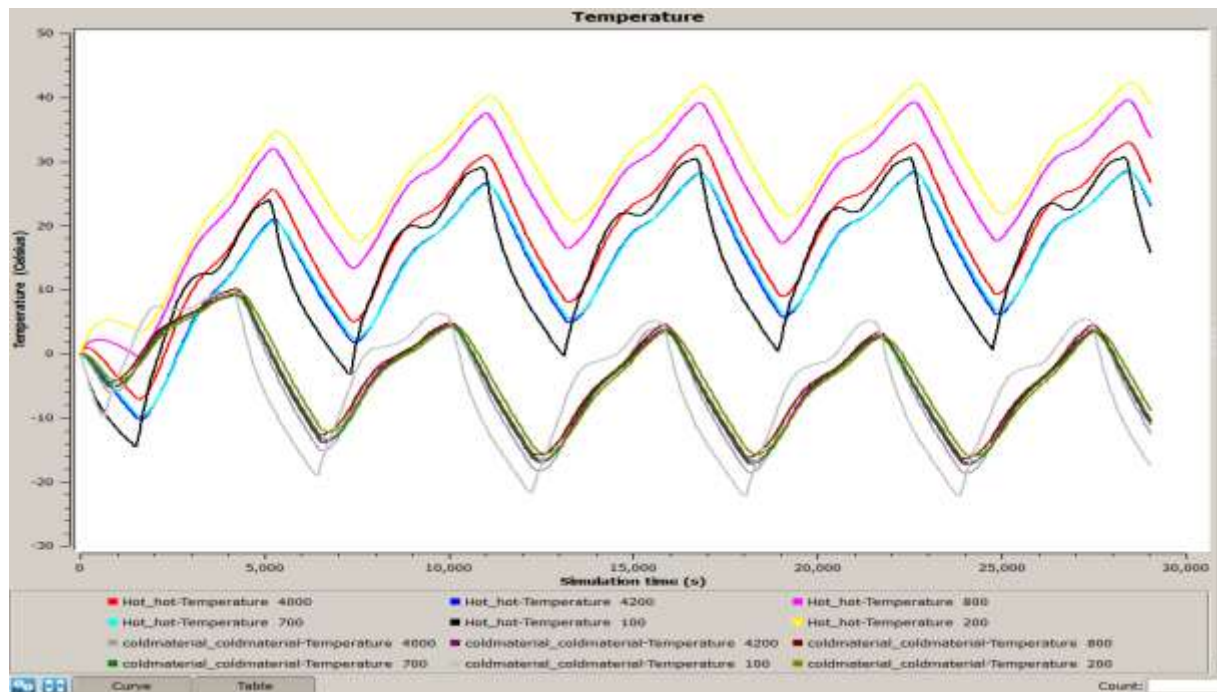
### **COLD CASE DIFFERENT SUBSYSTEMS:**



**Fig – 22: Temperatures of components for Cold case**

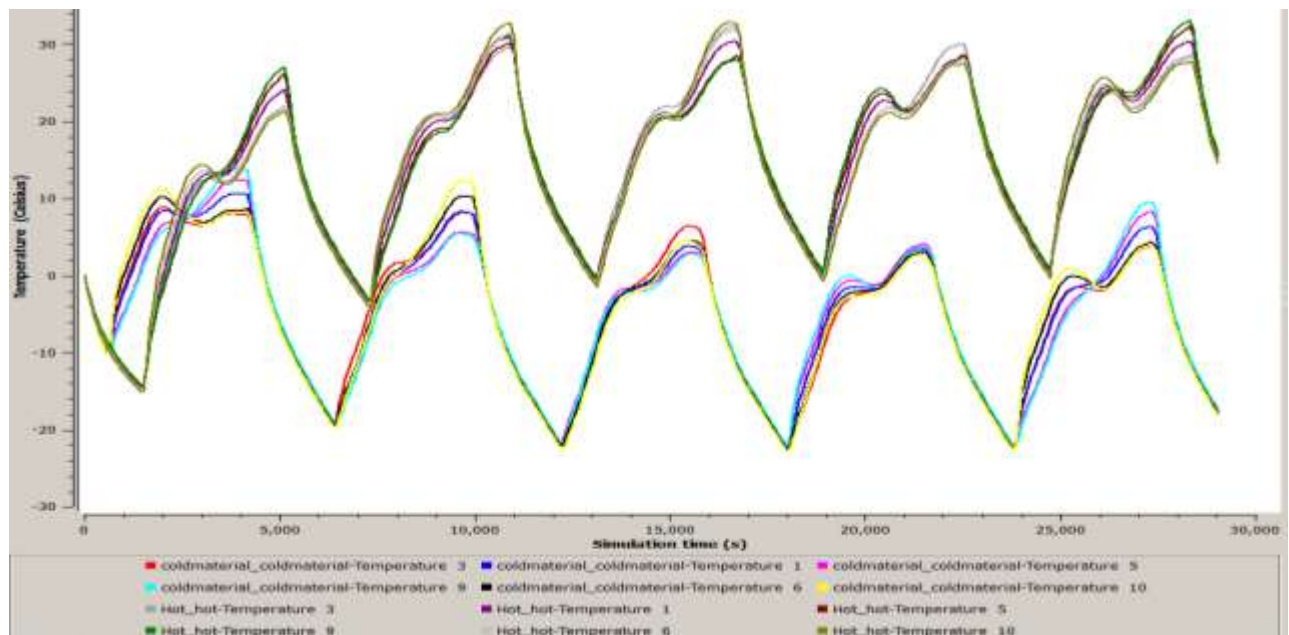


The above image shows that the maximum temperature reached was 10deg and the minimum temperature is -22deg. And the lowest temperature was recorded on the GPS Antenna.



**Fig – 23: Temperatures of components for Hot and Cold case**

The above image depicts the temperatures of all the important components of different subsystems which dissipate heat in both hot and cold cases.



**Fig – 24: Temperatures of Structure for Hot and Cold case**

The above image shows the temperatures of the Structure i.e Rails, Ribs and Sideframes for both hot and cold case. The extreme temperatures range from 35 deg to -22 deg. So this implies that there is a good conduction between the Solar Panels to the Structure which helps the Structure to not to reach the extreme temperatures.

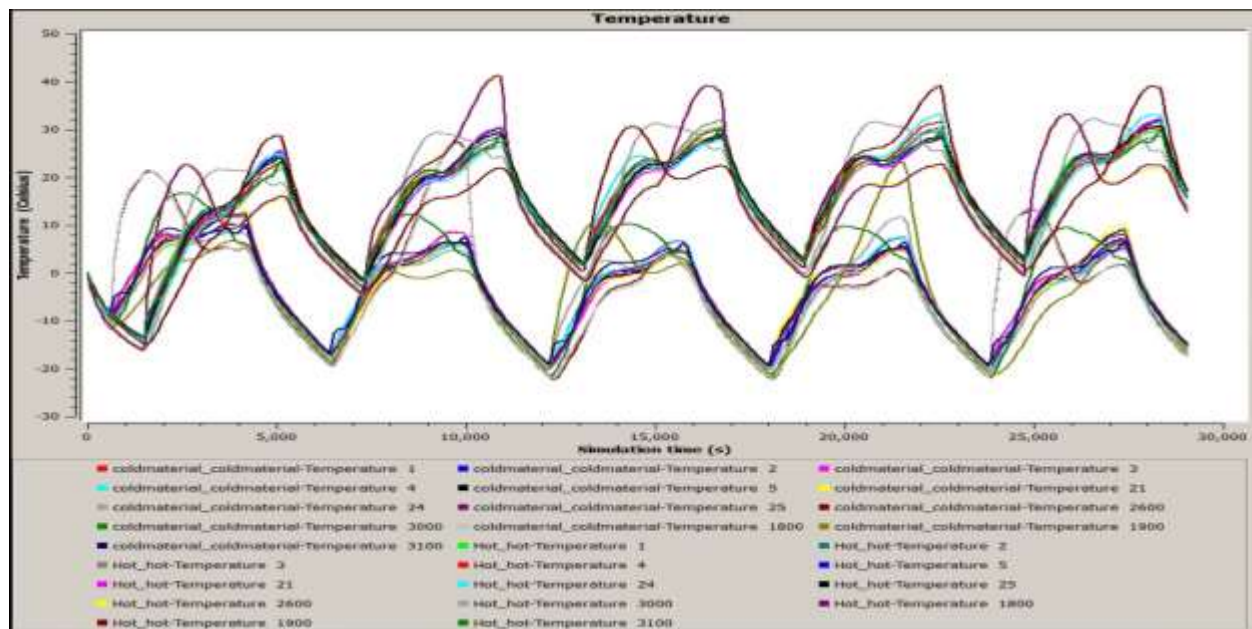
## 8. SENSITIVITY ANALYSIS OF RESULTS:

**8.1 Optical Properties:** The Optical properties of the Structure and the Solar panels were modified to the below values.

| COMPONENT       | ABSORPTIVITY |      | EMISSIONITY |      |
|-----------------|--------------|------|-------------|------|
|                 | OLD          | NEW  | OLD         | NEW  |
| SOLAR PANEL PCB | 0.79         | 0.77 | 0.91        | 0.81 |
| STRUCTURE       | 0.86         | 0.65 | 0.86        | 0.82 |

**Fig – 25: Optical Properties of important Subsystems**

For PCB, for old values correspond to the suggested values by CNES Thermal Engineer and new values correspond to the Epoxy Aluminum Paint which was a conductive paint mentioned in the reference by NASA.



**Fig – 26: Temperature changes with new optical properties for hot and cold case**

The above image shows the results of temperatures after changing the optical properties. But it's clearly evident that the minor change in optical properties does not have much effect neither on the Panels nor on the Structure.

## 8.2 SPIN RATE:

The maximum spin rate would be **1.5 revolutions per hour** that the Satellite will have in its orbit as suggested by the GPS team. The reason behind choosing this value was that if the spin rate increases more than this value, the objective of the payload, GPS Antenna, cannot be achieved.

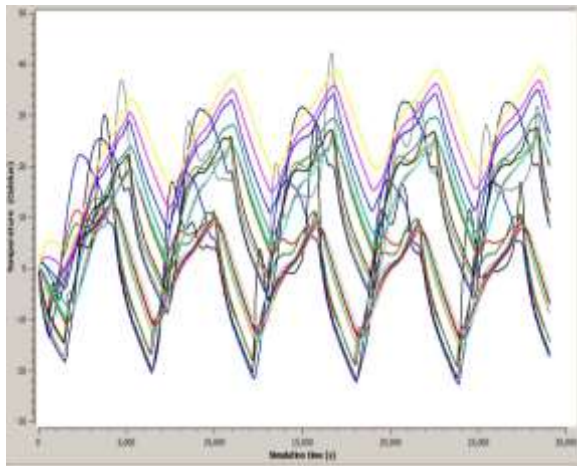


Fig-27 With old spin (1.5rev/hr) for hot & cold case

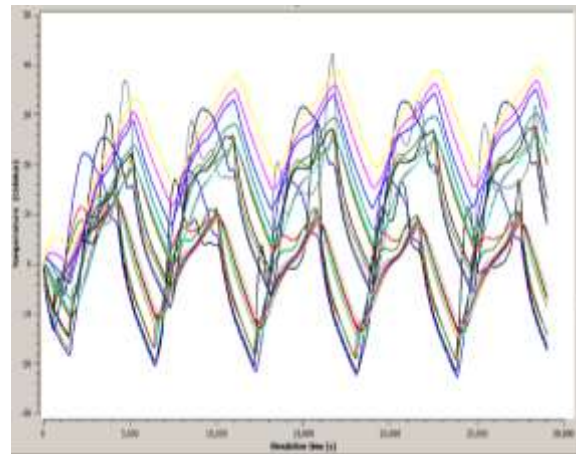


Fig-28 With new spin (0.15rev/hr) for hot and cold case

It's evident that there is not much difference in the temperatures of the components since the finalized spin rate is 0.15 rev/hour. The left side results were simulated with a speed of 1.5 rev/hour whereas the right side one were at a speed of 1 rev/hour.

## 8.3 NO CONDUCTION FROM PANELS TO STRUCTURE:

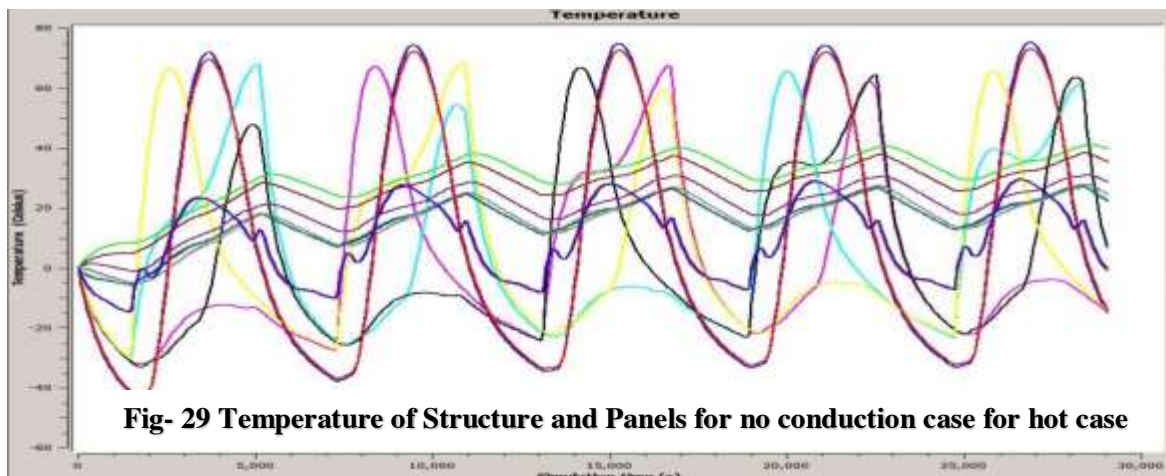
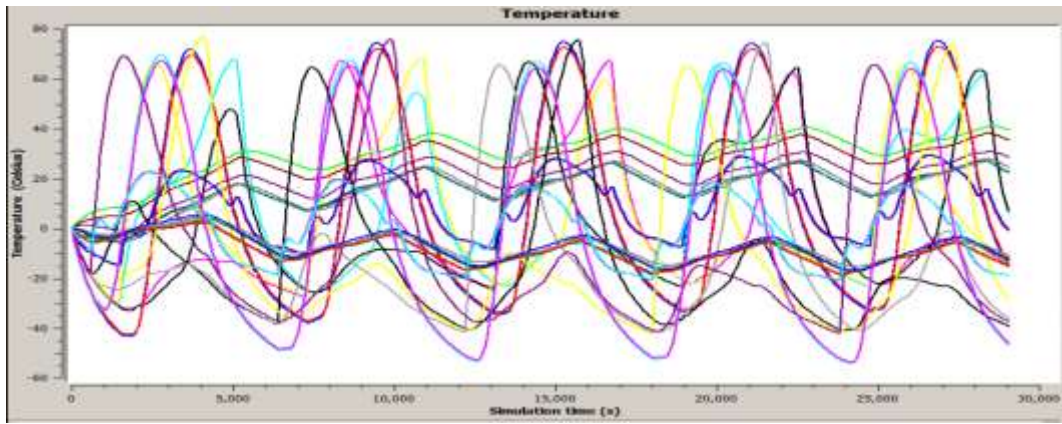


Fig- 29 Temperature of Structure and Panels for no conduction case for hot case



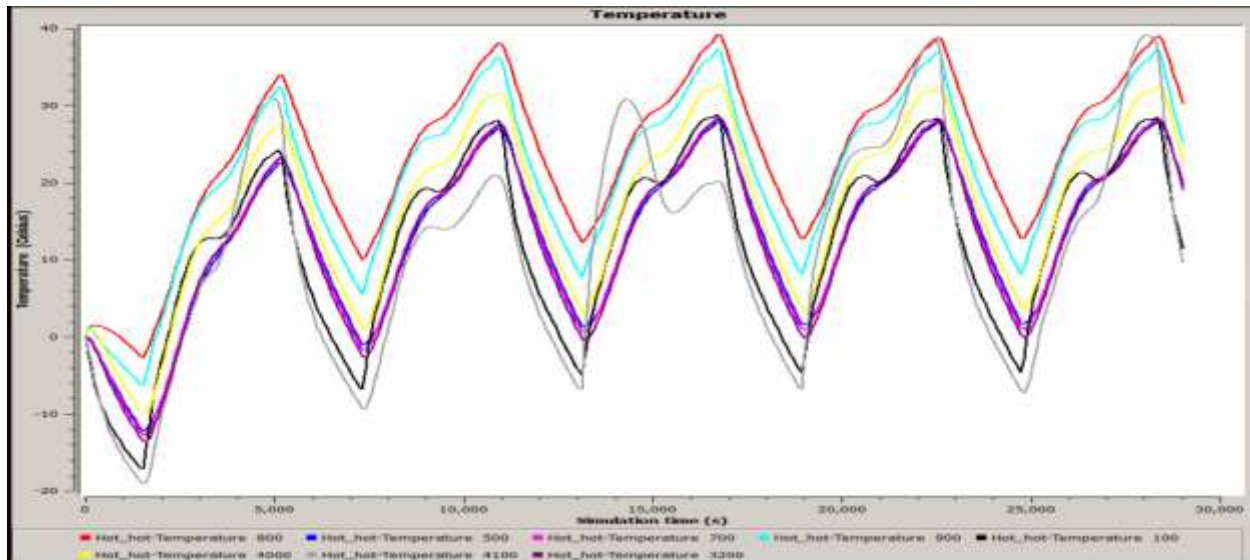


**Fig- 30: Temperature of Structure and Solar Panels when there is no conduction for both hot and cold case**

It's clearly evident that the temperatures reached 80°C in the hot case and -60 °C in the cold case. This implies that conduction is necessary to equalize the temperatures throughout the structure as well as to take the heat dissipated from the components. So there must be maximum conduction between Solar cells and the Panels as well as between the Solar Panels and the Structure or else the temperatures may go even greater than 100 °C or -80°C.

#### **8.4 PCB HEAT CAPACITY:**

Since the PCB is the most important component of the Satellite and most of the subsystems are modelled as PCB with varied thickness there is a necessity to input the exact material properties to get the appropriate temperatures. And the PCB properties vary with respect to the manufacturer. The Specific Heat Capacity is very important to calculate the Thermal Capacitance and this value is not at all available. But a heat transfer expert Ake Malhammar has provided with the PCB's Specific Heat Capacity as well as with the Thermal Conductivity and density. Since we already have the PCB with us so we have calculated the density by measuring the mass, the density value given by Malhammar matched with the calculated value. So the Heat Capacity was given as 1200J/kg-K. Since the CNES Thermal Engineer suggested to use the value 600 J/kg-K and also to perform sensitivity analysis and mentioned that there would not be much difference. Comparing the figure 23 and 24 with the below figure 31 it was evident that there is not much difference with the change in the PCB's thermal conductivity.



**Fig- 31: Temperature of components for hot case with new thermal conductivity of PCB**

## 8.5 FUTURE WORKS TO DO:

1. Justification of the results either by practically testing them using Thermal Vacuum and Cycling tests or using another solving method in Matlab or Ansys.
2. Radiation effects also should be included in the Thermal Analysis although it's very complex since it would bring more appropriate and approximate results.

To estimate this radiation effects some simpler methods to be adapted and it should be done component wise or else the result will be difficult to analyze if multiple components will be tested at a time.

3. Since the Sun sensors and Earth Sensors location has not been finalized yet they have not been included in the Thermica analysis. They may record the extreme temperatures depending on their location and so should not be neglected.
4. Since the battery temperatures are low in cold case a battery heater is recommended. Also in the datasheet of the battery it's clearly mentioned that the battery provides it maximum efficiency when it operates in the temperature range of 10°C and 50 °C. The battery heater was designed in ANSYS but it was not modelled in Thermica. So it should be modelled and the analysis should be performed again to ensure the maximum efficiency of battery.

## **9. VIBRATIONAL ANALYSIS & TESTING:**

It is mandatory to perform the Mechanical tests on the Satellite and Vibrational test is one of them. Along with the tests, Vibrational analysis is performed in any computational software to make sure that it survives the launch and entry conditions into the Space Environment. So it's very important to perform this analysis as well as the tests on the Satellite before launch. First Finite Element Simulations are to be performed since its mandatory as well as will be helpful in determining the Natural Frequency of the Satellite when performing Resonance Survey for the first time.

### **9.1 TESTING REQUIREMENTS:**

The tests to be performed on the Satellite have some requirements for qualification as well as for acceptance and proto-flight.

The Qualification tests are performed on the STM Model of the CubeSat.

#### **TESTING ORDER ADAPTED BY IGOSAT:**

1. Resonance Survey
2. Quasi- Static
3. Resonance Survey
4. Sinusoidal
5. Resonance Survey
6. Random Vibration
7. Resonance Survey

Resonance Survey is performed at the end to make sure that none of the components got loose or detached. This can be confirmed by the shift in the curve i.e if the curve shifts more that +5% or - 5% of the resonance frequency obtained when the survey was performed first then it implies that some of the parts may be detached or got loose.

We have adapted the above procedure but the original procedure recommended by the QB50 Acceptance checklist is that RESONANCE SURVEY should be performed at the beginning and after the Random Vibration Test. The reason for adapting the above procedure is that it will be easier to identify which test is responsible for the failure of vibration test and take precautions for

the next time to avoid it. And another reason is that the shift will determine the Satellite behaviour towards the test and also explains which more vulnerable condition is.

## **9.2 COMPUTATIONAL ANALYSIS IN ANSYS:**

### **MODELLING:**

A simple model is to be built specially for the Vibrational Analysis since the final CAD model of the CubeSat will be complex to mesh and takes a lot of time to obtain the results. Since the tests will be performed on the STM Model we can use dummy masses of the components with the available material which suits the properties of the majority of the components of the Satellite.

For IGOSat as the complete structure is made with Aluminium 2017 and since it's easily available the dummy masses are made with this material.

### **9.3 MATERIAL PROPERTIES:**

Since the properties of Aluminium 2017 T4 are not in the ANSYS material database so, the following properties were input in and created.

#### **ALUMINIUM 2017 T4:**

Density -  $2790 \text{ Kg/m}^3$

Young's modulus -  $7.2\text{E}10 \text{ Pa}$

Poisson's Ratio - 0.33

#### **FR-4 PCB:**

The PCB chosen was FR-4 which is Reinforced Epoxy with glass and is flame resistant (FR).

The properties input in ANSYS are:

Density -  $1850 \text{ Kg/m}^3$

Young's modulus -  $2.4\text{E}10 \text{ Pa}$

Poisson's Ratio - 0.12

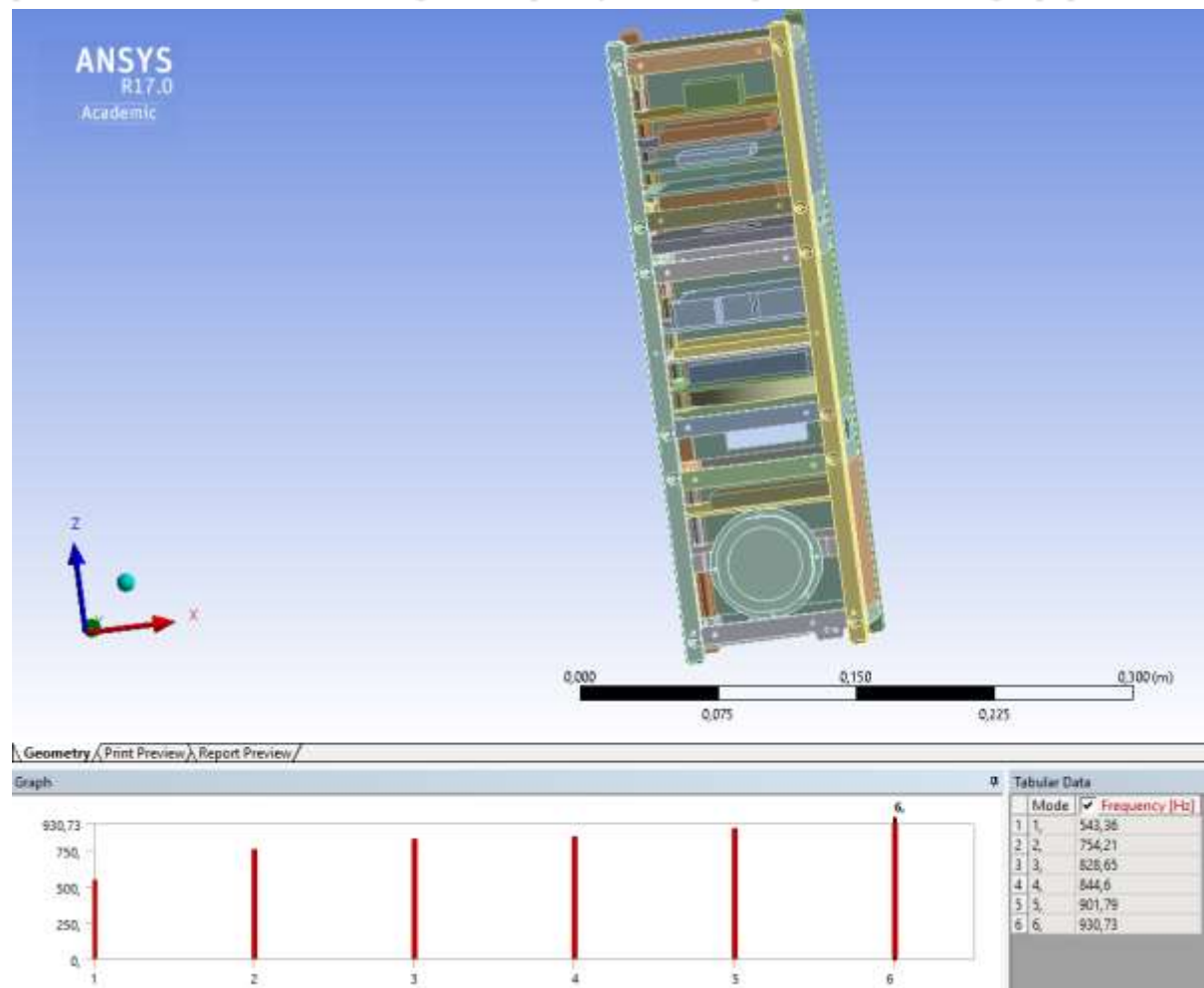


## 9.4 MODAL ANALYSIS:

### GEOMETRICAL CONSTRAINTS:

Since the Satellite will be in a pod or deployer the bottom of the panel is fixed and the top of the Satellite is free to have displacement in Z axis since it is inside the pod which constraints the other two axis.

To obtain the resonance frequency the Modal analysis is performed. So the following image shows the obtained resonance frequency for the IGOSat which is 543.36Hz. This analysis was performed without the limit range of frequency since it depends on the testing equipment.

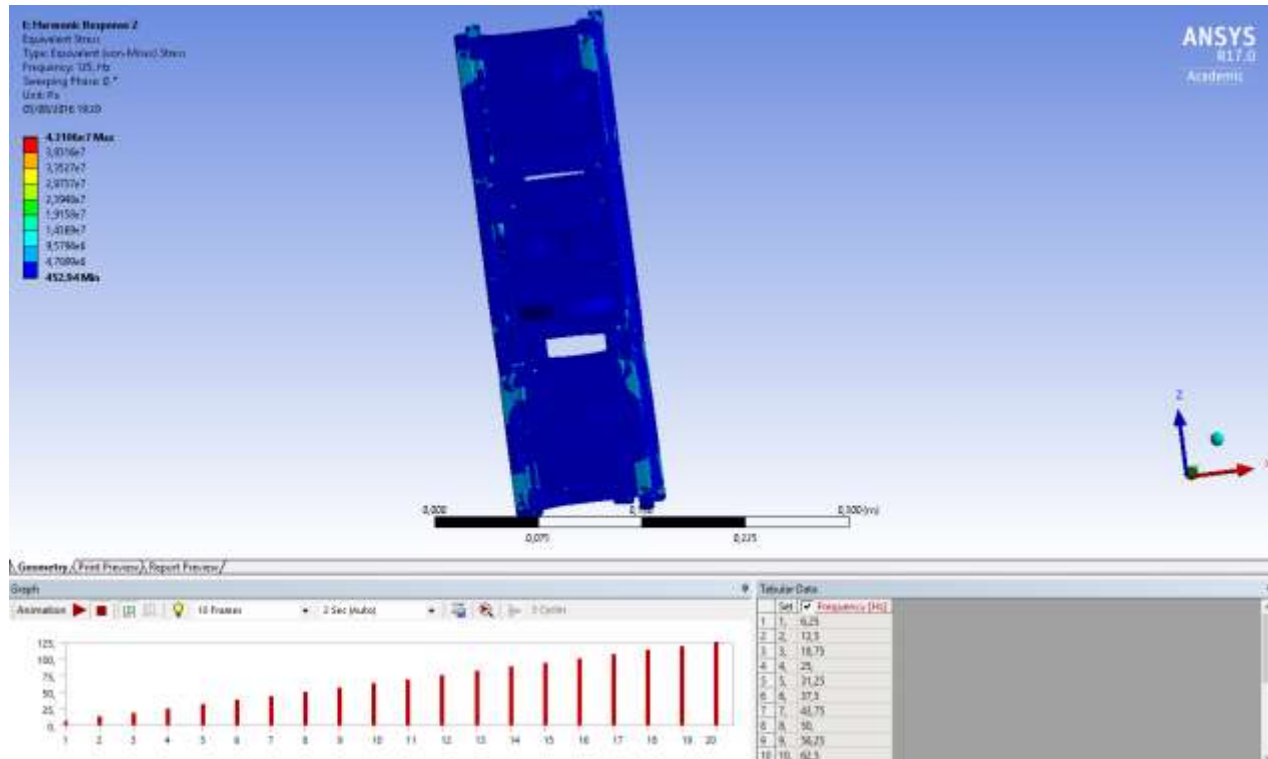


**Fig-32: Modal frequencies obtained for Z - axis in ANSYS 17**

Due to time constraints this test was performed only in the Z-axis but it should be performed for all the axes so that they can be verified with the STM testing results.

## 9.5 HARMONIC ANALYSIS: SINUSOIDAL VIBRATION

This analysis is also known as the Sinusoidal Vibrational analysis since the amplitude is similar to the sine curve. This test is done on the Satellite to understand the steady state behaviour. The amplitude is same as mentioned in the QB50 requirements document.



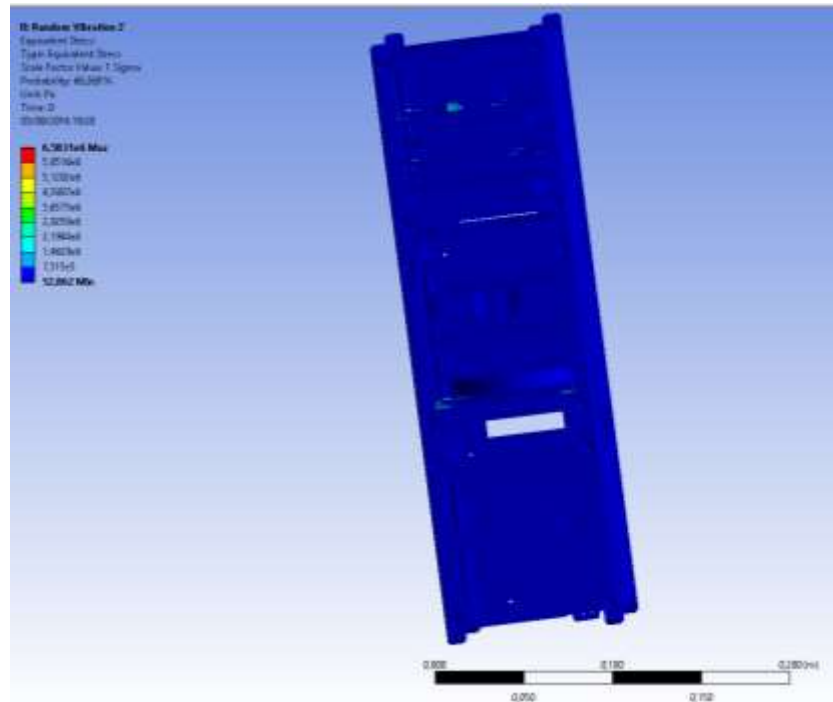
### Fig-33: Equivalent Stresses in Sinusoidal Vibration in ANSYS17

The maximum obtained Stress on the Satellite is approximately 0.5MPa which is far less compared to the Yield Strength of the material chosen for the component. So this implies that there will be no plastic deformation.

## 9.6 RANDOM VIBRATIONAL ANALYSIS:

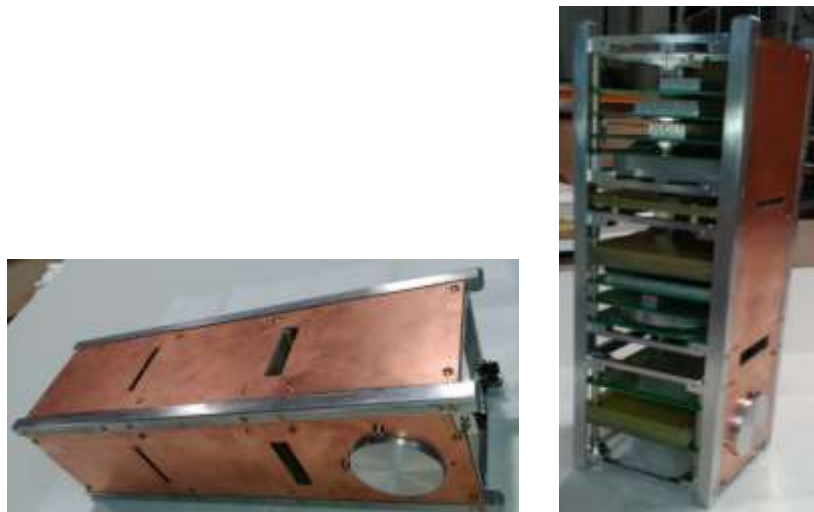
The name itself implies that test is done at a random frequency. But the RMS acceleration is 8.03g. This analysis has been done for the X, Y and Z axis.

In CubeSat requirements the corresponding frequency as well as amplitude has been given but there seems to be a correction in it. Since it leads to the RMS acceleration greater than the above value which is 8.03g. The maximum obtained Stress on the Satellite which is approximately 7MPa which is far less compared to the Yield Strength of the material chosen for the component. So this implies that there will be no plastic deformation.



**Fig-34: Equivalent Stresses in Random Vibration in ANSYS17**

## 10. VIBRATIONAL TESTS OF IGOSat:



**Fig-35: Structural and Thermal Model of Igosat**

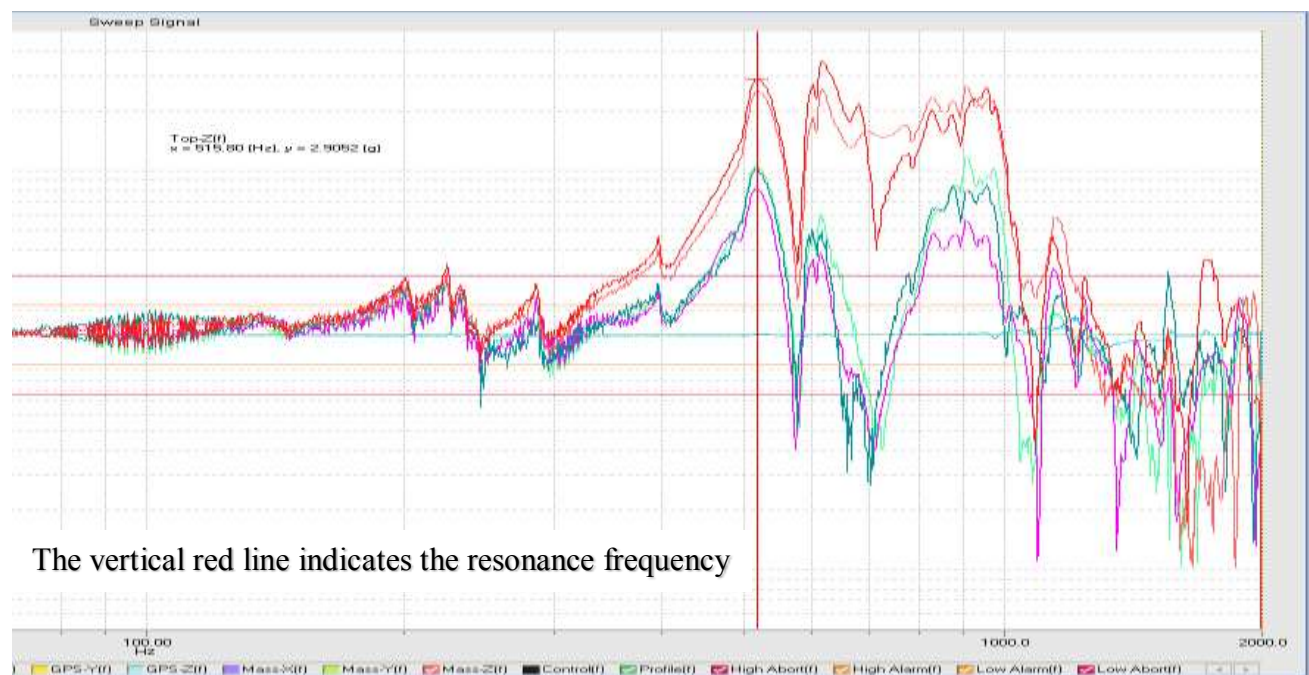
The above images show the assembly of the STM model of the IGOSat. After assembling all the parts, the dimensions were checked using Digital Height Measuring Gauge as well as with the Co-Ordinates Measuring Machine to ensure that the Satellite fits into the Pod without any problem like last year.

The below image shows that the Satellite was on a shaker pot on which the test was performed. The Satellite was first integrated into the Pod and then accelerometers were glued to the Satellite at different positions in different cubes.



**Fig-36: Shaker Pot with Igosat assembled in Pod**

#### **RESONANCE SURVEY:**

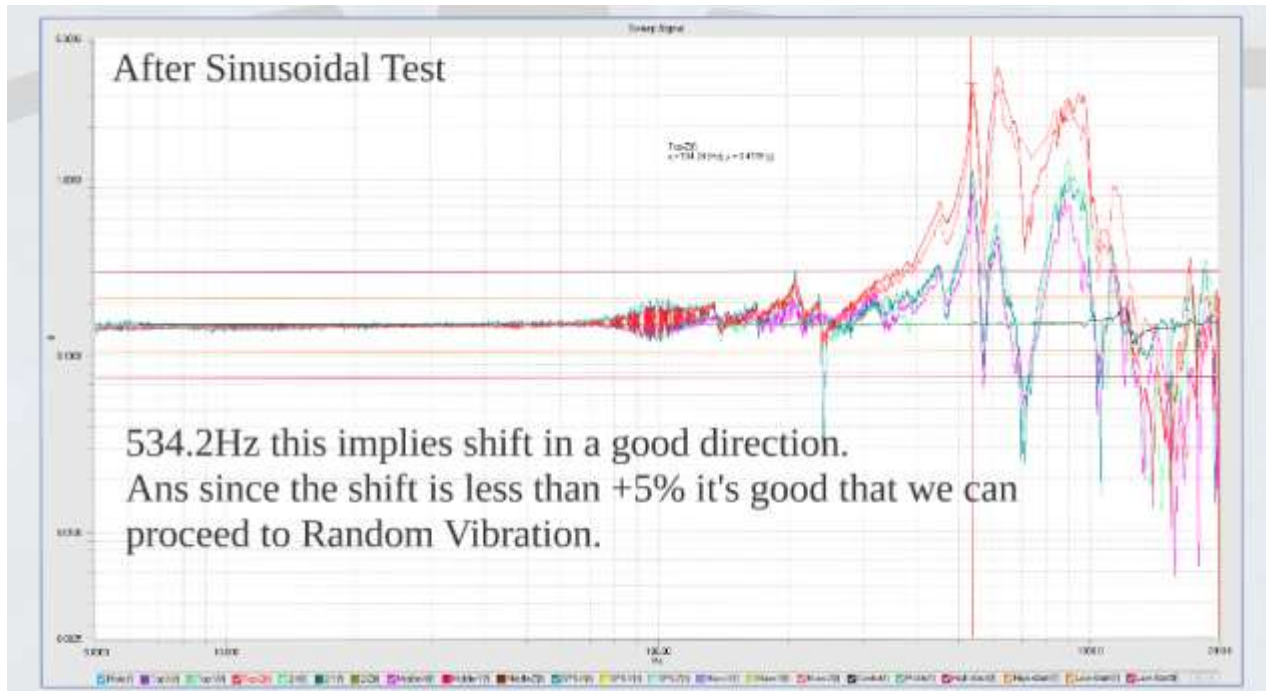


The vertical red line indicates the resonance frequency

**Fig-37: Results for resonance survey in Z - axis**



It is observed that the resonance frequency is obtained at 515.8Hz in Z-axis which is very close to the value obtained in the Modal Analysis performed in ANSYS 17 which is 543.36Hz. So this implies that the analysis results and test results are in good agreement.



**Fig-38: Resonance survey results (5<sup>th</sup> run) after Sinusoidal vibration in Z - axis**



**Fig-39: Resonance survey results (7<sup>th</sup> run) after Random vibration in Z – axis**

From the above results, the IGOSat successfully cleared the vibration qualification test in Z-axis.

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## APPENDIX 1: NODES REPRESENTATION:

|             |            |                                  |
|-------------|------------|----------------------------------|
| GPS         | 4100       | Antenna without PCB              |
|             | 4000       | Receiver PCB                     |
| COM         | 100        | Antenna                          |
|             | 200        | Radio card                       |
| SCI         | 500        | PCB                              |
|             | 400        | SiPM                             |
|             | 300        | Inner Crystal (CeBr3)            |
|             | 700        | Easiroc Board                    |
|             | 600        | Outer Plastic(BC-412)            |
| OBC         | 800        | computer Board                   |
| ADCS        | 900        | Torquer Board                    |
|             | 1000       | Torquer 1                        |
|             | 1100       | Torquer 2                        |
|             | 1200       | Torquer 3                        |
|             | 1300       | Magnetometer (OLD)               |
|             | 1400       | Sun+Y (OLD)                      |
|             | 1500       | Sun -Y(OLD)                      |
|             | 1600       | Sun +X(OLD)                      |
| EPS         | 1700       | Sun -X(OLD)                      |
|             | 4200       | EPS Board                        |
| POWER       | 3200       | Battery PCB                      |
|             | 3300-3600  | Battery Cell 1,2,3,4 (incl conn) |
| SOLAR CELLS | C4300-5500 | Bottom cube                      |
|             |            | Middle cube                      |
|             |            | Top cube                         |
|             |            | Top side                         |
|             |            | Bottom side                      |
| PANELS      | C1800-3100 | 1 panel for 1U CUBE mass         |
|             |            | 1 panel for 1U CUBE mass         |
|             |            | 1 panel for 1U CUBE mass         |
|             |            | Top panel                        |
|             |            | Bottom panel                     |
| EMPTY       | C3700      | Empty Board                      |
|             | C3800      |                                  |
|             | C3900      | Mass balancer                    |