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# Impact of orbit inclination on heat transfer in a 1U LEO CubeSat

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**Abstract.** Temperature prediction is crucial to build dependable CubeSats and operate them at peak efficiency. Therefore, all parameters that could impact the thermal performance of the satellite must be taken into account in the thermal analysis. This work covers the thermal simulation of a 1U CubeSat. The objective is to simulate, using the commercial software COMSOL Multiphysics, the impact of an important parameter on the satellite's temperature distribution: beta angle. It defines the position of the CubeSat relatively to the solar vector. To investigate the effect of this parameter on the satellite, a set of simulations was performed for different beta angles.

## 1 Introduction

Before a satellite is launched, the various scenarios it will face in orbit must be analyzed and tested in order to reduce the occurrence of failures or inefficient performance. This is also critical for CubeSat projects, a category of satellites that relies on the $10 \times 10 \times 10\, cm$ dimensions of the standard 1U design.

The majority of CubeSats in Low Earth Orbit (LEO) are situated at an altitude under $600 km$. They have a quasi-circular orbit and a period of approximately $100 min$. Since the orbiting satellite is subjected to external radiation from space, as well as heat generated by its internal components. This radiative environment produces extreme variations in the temperature of the satellite, for which maintenance is essential for the operation of the electrical components and therefore for the success of the mission.

The determination of the temperature distribution in orbit allows the proper selection of thermal control equipment by preventing high temperature gradients. Consequently, the primary purpose of thermal control is to study the temperature of the satellite, design thermal control mechanisms, and test the proposed solution [1-2].

The direct solar radiation, the Earth's albedo (the reflection of sunlight by the Earth), and the Earth's infrared emissions are the three main sources of external heat for satellites in low Earth orbit (LEO). These sources can be considered to remain constant all along the orbit for practical applications involving spacecraft heat transfer. However, this is not always the case for the position and orientation of the satellites, In addition, the orbital settings and the attitude of the satellite will determine the amount of irradiation that reaches its surfaces, the eclipse period, the sides shadowed by the close vicinity and, as a result, the temperature range.

## 2 Orbit environment heating fluxes

The temperature of the CubeSat is the result of the heat fluxes it encounters in orbit. Thus, it varies according to the orbital settings (attitude, inclination, beta angle, orientation...), the spacecraft geometry, materials and the properties of the surface. In order to determine the temperature of the CubeSat, the heat balance must be implemented to consider all the energy that enters and leaves the system. The overall energy balance of the Cubesat in transient regime is as follows [2].

$$Q_{solar} + Q_{albedo} + Q_{IR} + Q_{gen} - Q_{rad} = m C_{avr} \frac{dT_{avr}}{dt} \quad (1)$$

where $Q$ is a heat flux, $m$ is the mass, $C_{avr}$ is the average specific heat, $T_{avr}$ the average temperature. The index $IR$ designates terrestrial Infra-Red radiation, $rad$ is for the CubeSat radiated heat and $gen$ is for heat generated inside it.

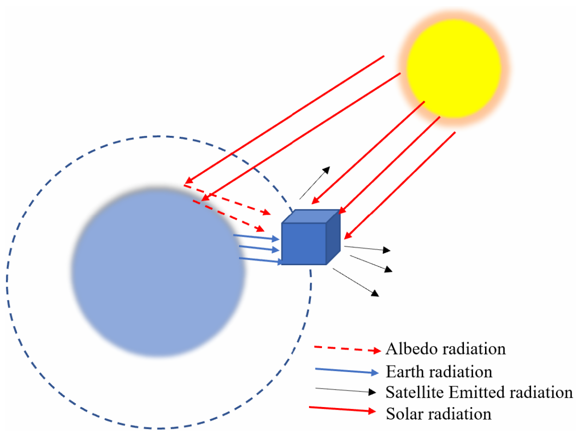


**Fig. 1.** Heat exchange between the satellite and the environment space.

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Further explanations of each term in Eq. (1) are provided in the sections that follow [1-2].

Fig. 1 illustrates the heat exchange taking place between the system CubeSat and the rest of space.

### 2.1 Solar radiation

Solar radiation refers to the amount of energy emitted by the Sun in electromagnetic waves. It is characterized by the solar flux, also known as the solar constant whose average value is estimated at 1367 $W/m^2$. At a distance of 1AU (Astronomical Unit) from the Sun, it can be assumed that the Sun's rays are parallel to the Earth.

The solar radiation that reaches the exterior surfaces of the CubeSat in this study will be as follows:

$$Q_{solar} = \alpha_s \, A_{sun-sat} \, S \tag{2}$$

where $\alpha_s$ is the solar absorptivity of the surface, $A_{sun-sat}$ is the surface of the CubeSat exposed to the solar radiation ($m^2$) and $S$ the solar constant $1367 W/m^2$.

### 2.2 Albedo radiation

The albedo is the quantity of solar radiation that the Earth reflects. The assumption is that it belongs to the same spectrum as solar radiation and is frequently specified as a percentage of the solar constant, called the albedo factor. Numerous factors, including the conditions of the atmosphere, the ground areas and the clouds, all affect the Earth's albedo which is set at 0.3 on average.

The albedo radiation that reaches the exterior surfaces of the CubeSat in this study will be as follows:

$$Q_{albedo} = \alpha_s \, A_{earth-sat} \, S \, a \, F_{sat-planet} \tag{3}$$

where $A_{earth-sat}$ the surface of the CubeSat exposed to the albedo radiation ($m^2$), $a$ the albedo factor and $F_{sat-planet}$ the view factor seeing between the CubeSat and the Earth surfaces.

### 2.3 Earth radiation

The average value of the terrestrial flux $Q_E$ is $240 W/m^2$ since the infrared radiation that the Earth emits is assumed to be diffuse and globally identical to that of a black surface at about $-20°C$. Since the spectrum of terrestrial radiation is in the same band as that normally emitted by satellites, the fraction of the incident terrestrial flux absorbed by a satellite's radiator is its emissivity.

The Earth radiation that reaches the exterior surfaces of the CubeSat in this study will be as follows:

$$Q_{IR} = \alpha_{IR} \, A_{earth-sat} \, Q_E \, F_{sat-planet} \tag{4}$$

where $\alpha_{IR}$ is the absorptivity of the Earth's IR radiation and $Q_E$ the infrared energy emitted by the Earth ($W/m^2$).

### 2.4 CubeSat's emission

Without the ability to dissipate thermal energy, the temperature of the CubeSat would rise until a critical failure occurred. Under terrestrial environmental conditions, objects are cooled by the surrounding atmosphere through convection. This mechanism is not possible in space conditions. It is recommended to operate the satellite in a temperature range similar to Earth conditions, around $20°C$. Therefore, the radiation will be in the infrared spectrum. Infrared radiation will be emitted into space from the outer surfaces of the spacecraft and from any additional radiators.
The emitted radiation is:

$$Q_{rad} = \varepsilon \, \sigma T^4 \, A_{tot} \tag{5}$$

where $\varepsilon$ is the emissivity of the infrared radiation, $T$ temperature of the CubeSat, $\sigma$ the constant of Stefan-Boltzmann ($=5.670374\times10^{-8} W/m^2/K^4$) and $A_{tot}$ the total surface of the CubeSat ($m^2$).

### 2.5 Generated heat flux

Internal heat generation was ignored in this study.

## 3 CubeSat thermal Analysis

The thermal analysis of the CubeSat requires the determination and verification of the temperature limits encountered with the hypotheses that will be discussed in the following sections.

### 3.1 Beta angle

A preliminary way to visualize the global radiation environment to which an orbiting satellite is subjected is to refer to the angle β of the orbit, which is given as the angle between the orbit plane and the solar vector of any Earth-orbiting body, as illustrated in Fig. 2. It identifies how long the CubeSat is exposed to direct solar rays.

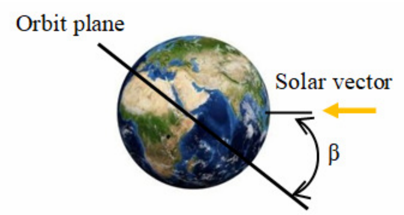


**Fig. 2.** Illustration of beta angle.

The beta angle ranges from $-90°$ to $+90°$ depending on the satellite orientation. When viewed from the Sun, the beta angle is negative when the satellite rotates clockwise and positive when the satellite rotates counterclockwise. By varying the beta angle, the orbit plane will have different orientations with respect to the Sun and the Earth, which results in different temperature intervals. The significance of the beta parameter with the previously mentioned radiation sources was used for the temperature estimation in this work.

## 3.2 COMSOL Multiphysics Simulation

### *3.2.1 Geometry*

The geometry represents a 1U CubeSat, $10\times10\times10\,cm$, six solar panels coating its external sides, a battery, four PCBs and bolts that create a thermal conduit linking the top and the base of the CubeSat [3].

Since the aim of this work is a general simulation of a 1U CubeSat, all the specific details related to cabling, electronics and connectors have not been included in the modeling.

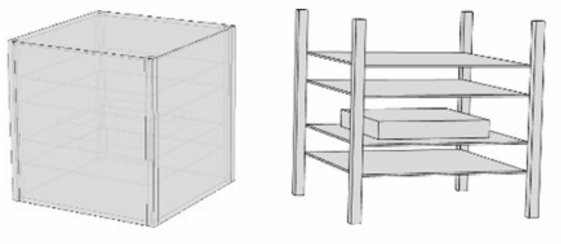

**Fig. 3.** External and internal structure of the CubeSat.

### *3.2.2 Meshing*

The meshing was done by the built-in mesher. The size of the elements has been set to fine. The complete mesh consists of 123310 elements.

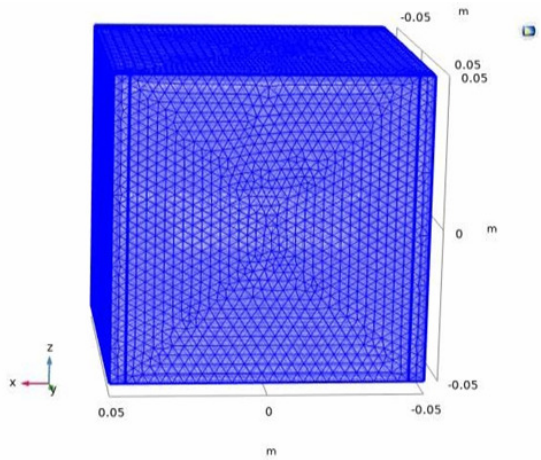


**Fig. 4.** The Meshed geometry on COMSOL.

### *3.2.3 Material properties*

The material properties are summarised in Table 1 and Table 2. The following notations are used: $\rho$ is the mass density, $c$ the specific heat and $\kappa$ the thermal conductivity.

**Table 1.** Material thermal properties of the 1U CubeSat.

| | $\rho(kg/m^3)$ | $c(J/kg/K)$ | $\kappa(W/m/K)$ |
|---|---|---|---|
| Solar panels | 2325 | 1103 | 1.03 |
| Bolts | 2810 | 948 | 140 |
| PCB | 2120 | 975 | 0.64 |
| Battery | 2247 | 1110 | 23 |

**Table 2.** Thermo-optical properties of the 1U CubeSat.

| | |
|---|---|
| Solar absorptivity $\alpha_s$ | 0.87 |
| IR absorptivity $\alpha_{IR}$ | 0.8 |
| IR emissivity $\varepsilon$ | 0.81 |

### *3.2.4 Boundary conditions*

The thermal boundary conditions are given in Table 3.

**Table 3.** Thermal boundary conditions.

| | |
|---|---|
| Solar flux ( $W/m^2$ ) | 1367 |
| Earth flux ( $W/m^2$ ) | 240 |
| Albedo coefficient | 0.3 |

The CubeSat will be subjected to a significant variation in incoming radiation $Q_{solar}$ as shown in Fig. 5.

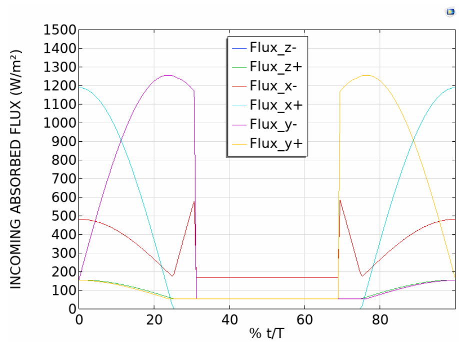


**Fig. 5.** Thermal radiation reaching the CubeSat sides for $\beta = 0$ .

The thermal irradiance entering each face of the CubeSat is plotted in the graph above. As can be observed in Fig.5, there is a gap where the total heat flux absorbed stayed constant. During this period, the CubeSat was pointed towards the behind of the Earth and did not receive any heat flux coming from the Sun. The graph shows that the heat flux hitting the surfaces of the CubeSat increases and/or decreases cyclically according to the orbital position of the satellite.

The eclipse state, when only the Earth's emission is remaining, is the reason behind the gap in the middle of the graphic. On this orbit and in this attitude, the $Z^+$ and $Z^-$ faces are opposite to each other and receive the same amount of incoming radiation.

### *3.2.5 View factor*

In this work, the radiation between the inner surfaces of the cube is not considered. The analytically calculated view factors in the above table are between the external surfaces of the CubeSat and the earth [3].

The CubeSat is oriented so that the $X^+$ side of the cube is facing the sun, and the $X^-$ side is facing the earth.

**Table 4.** The view factors values.

| | | |
|---|---|---|
| IR radiation | $F_x$ (Earth direct face) | 0.8773 |
| | $F_{yz}$ (Earth side face) | 0.2816 |
| Albedo radiation | $F_y^-$ | $Max(0, F_{yz}\cos\beta)$ |
| | $F_x^-$ | $Max(0, F_x\cos\beta)$ |
| | $F_z^-$ | $Max(0, F_{yz}\cos\beta)$ |
| | $F_z^+$ | $Max(0, F_{yz}\cos\beta)$ |
| | $F_y^-$ | $Max(0, F_{yz}\cos\beta)$ |

### *3.2.6 Altitude and orbit*

The satellite describes a circular orbit, at an altitude of $431km$, which corresponds to a period of $5583s$.

The CubeSat will be subjected to a significant variation in incoming radiation

## 4 Results and discussion

Beta angle is a significant parameter that impacts the thermal behavior of the CubeSat. In order to explore its impact on the satellite, a set of simulations was performed with different beta angles.

In this work, the studied satellite has been analyzed in different beta angles ($0°, 40°, 80°$) in order to evaluate its impact on heat transfer and satellite temperature.

The simulation is done on 5 periods to reach the stationary regime, in $27900s$. The time advance has been set to automatic, with a step of $30s$ and a duration of five cycles.

After the 5 simulation periods, the results obtained during the last cycle are presented on the graphs below where the blue, green and red curves represent the variation of the satellite temperature for the respective angles $\beta = 0$, $\beta = 40°$ and $\beta = 80°$.

Below are the simulation results for the beta angle $\beta = 0$.

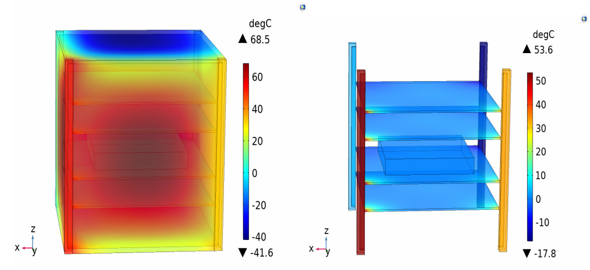

**Fig. 6.** The variation of temperature on the external and internal satellite structure for $\beta = 0$ at $27780s$.

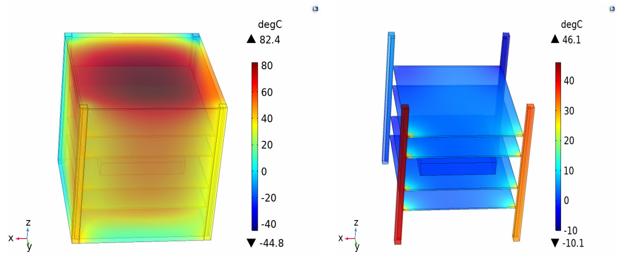

**Fig. 7.** The variation of temperature on the external and internal satellite structure for $\beta = 40°$ at $27780s$.

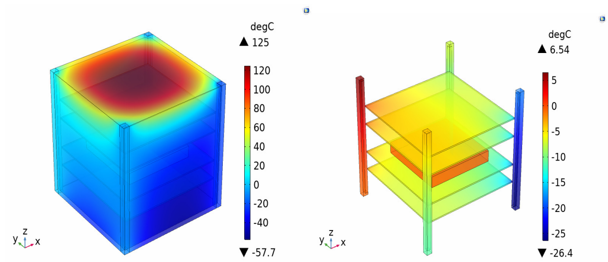

**Fig. 8.** The variation of temperature on the external and internal satellite structure for $\beta = 80°$ at $27780s$.

**Table 5.** CubeSat maximal and minimal temperature as function of the $\beta$ angle.

| | **Outer geometry** | | **Inner structure** | |
|---|---|---|---|---|
| $\beta$ | $T_{max}$ (°C) | $T_{min}$ (°C) | $T_{max}$ (°C) | $T_{min}$ (°C) |
| 0° | 70.4 | -41.4 | 58.1 | -14.6 |
| 40° | 82.7 | -45.3 | 47.7 | -8.65 |
| 80° | 125 | -57.7 | 6.54 | -26.4 |

Figures 6, 7 and 8 show the isovalues of temperature of the satellite for $\beta = 0$ after 5 periods, at $t = 27900s$.

Table 5 summarizes the internal and external temperature variation of the CubeSat.

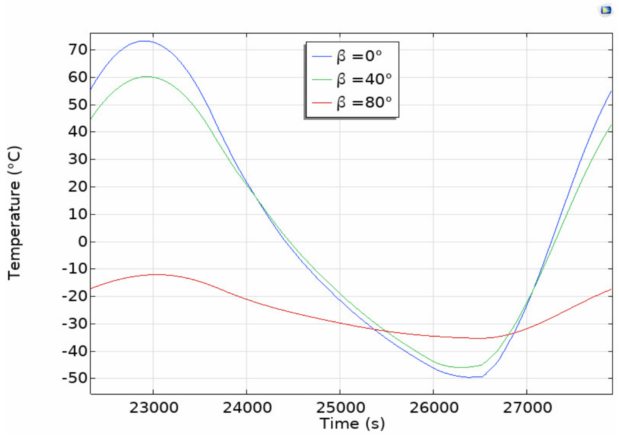


**Fig. 9.** Variation of temperature on the $X^+$ face versus time in the interval $[22500, 27900]s$.

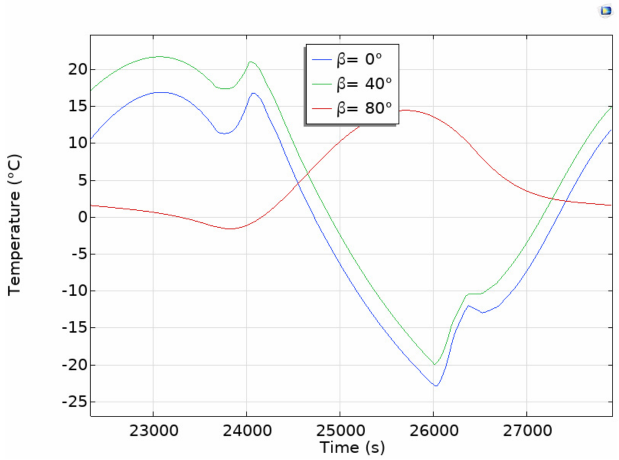


**Fig. 10.** Variation of temperature on the $X^-$ face versus time in the interval $[22500, 27900]s$.

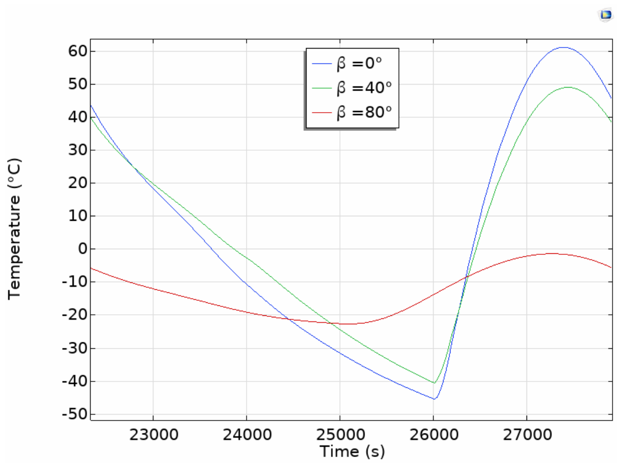


**Fig. 11.** Variation of temperature on the $Y^+$ face versus time in the interval $[22500, 27900]s$.

Figures 9 to 14 give, for every face of the satellite, the evolution of temperature versus time, as a function of the beta angle. At $\beta = 0$, the $X^+$ side is fully exposed to the sun while at $\beta = 80°$, the $Z^+$ side of the cube is the most subjected to the sun.

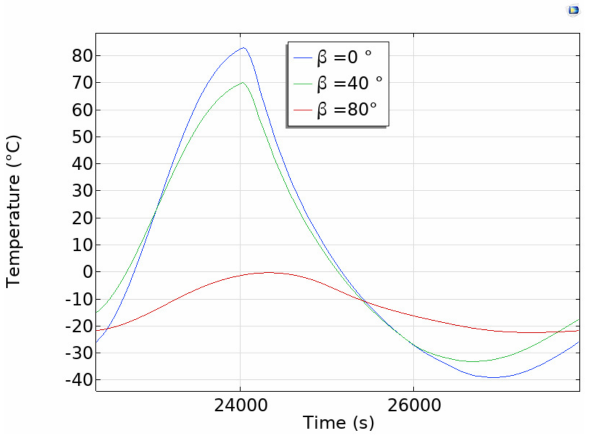


**Fig. 12.** Variation of temperature on the $Y^-$ face versus time in the interval $[22500, 27900]s$.

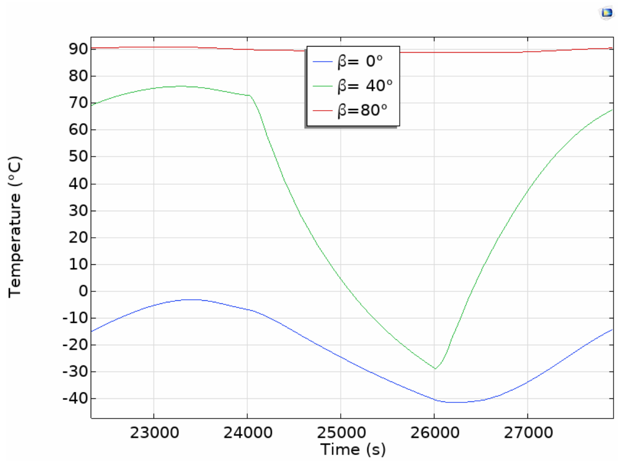


**Fig. 13.** Variation of temperature on the $Z^+$ face versus time in the interval $[22500, 27900]s$.

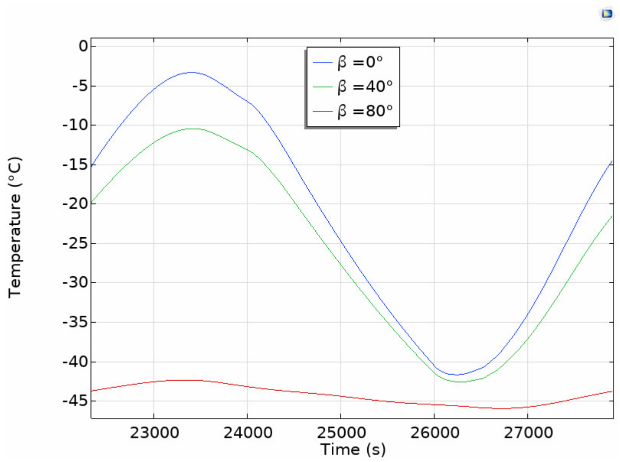


**Fig. 14.** Variation of temperature on the $Z^-$ face versus time in the interval $[22500, 27900]s$.

For the $\beta$ values 0° and 40°, the temperature of the sides of the satellite has changed over time. This is due to the fact that part of its time is passed under eclipse, whereas the remainder of the time it faces the light of the sun. However, for a beta value equal to 80°, the temperature of the satellite remained comparatively stable over the period since its orientation and position relative to the sun did not change. An orbit with $\beta$ equal to 0 will have the longest eclipse time because it is shaded by the full diameter of the Earth, as $\beta$ increases, the eclipse time decreases until $\beta$ equals $90°$, where the sunshine time is maximum.

## 5 Conclusions

In this work thermal simulation of a 1U CubeSat was performed by using COMSOL Multiphysics software. The impact of the orbit parameter, termed beta angle, which defines the position of the satellite with respect to the solar vector was investigated. The satellite's temperature distribution was calculated for different beta angles. After running a series of simulations, it is found that higher beta angles expose the satellite to prolonged sunlight heating as the satellite is subjected to longer periods of both direct solar radiation and albedo, resulting in a negative effect on the performance of the satellite's solar panels. It was shown that the impact of the beta angle on the temperature variation of each face of the CubeSat is important. Considerable temperature variations occur cyclically as the satellite is orbiting.

## References

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