

STUDENTS' SPACE ASSOCIATION

THE FACULTY OF POWER AND AERONAUTICAL ENGINEERING

WARSAW UNIVERSITY OF TECHNOLOGY



CRITICAL DESIGN REVIEW

THERMAL CONTROL SYSTEM

November 2016

Issue no. 1

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

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Abbreviated terms

ADCS – Attitude Determination and Control System

BW – Back Wall

CAM - Cameras

COMM – Communication System

EPS – Electrical Power System

DT – Deployment Team

FW – Front Wall

MA – Mission Analysis

MCS – Model Coordinate System

MLI – Multi Layer Insulation

OBC – On-board Computer

PCB – Printed Circuit Board

PS – Power Shortage

SunS – Sun Sensor

SKA – Students' Space Association (Studenckie Koło Astronautyczne)

TCS – Thermal Control System

TBD – To Be Defined

TBC – To Be Conducted

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This document describes the thermal analysis modelling and presents results that were performed for PW-Sat2 project, using ESATAN-TMS software. Its main objective is to show, whether the design does meet the thermal requirements and to present the proper thermal design, if required.

1.2 PROJECT DOCUMENTATION STRUCTURE

See section 1.3 in [PW-Sat2-C-00.00-Overview-CDR].

Reference Documents

- [1] Y. Kim, S. Mohan, J. B. Siegel, A. G. Stefanopoulou and Y. Ding, "The Estimation of Temperature Distribution in Cylindrical Battery Cells Under Unknown Cooling Conditions," *IEEE Transactions on Control Systems Technology*, vol. 22, no. 6, November 2014.
- [2] Y. A. Çengel, Heat Transfer: A Practical Approach, McGraw-Hill, 2003.
- [3] "ECSS-E-ST-10-03C Space engineering - testing," ESA Requirements and Standards Division, Noordwijk, 2012.
- [4] "ECSS-E-ST-10-06C Space engineering - Technical requirements specification," ESA Requirements and Standards Division, Noordwijk, 2009.

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2 MODEL CONFIGURATION & THERMAL REQUIREMENTS

2.1 COORDINATE SYSTEM

The coordinate system used in ESATAN-TMS is shown at the Figure 2-2. The 'p' (plus) and 'm' (minus) notation was used to describe the position of the component relative to the coordinate system origin.

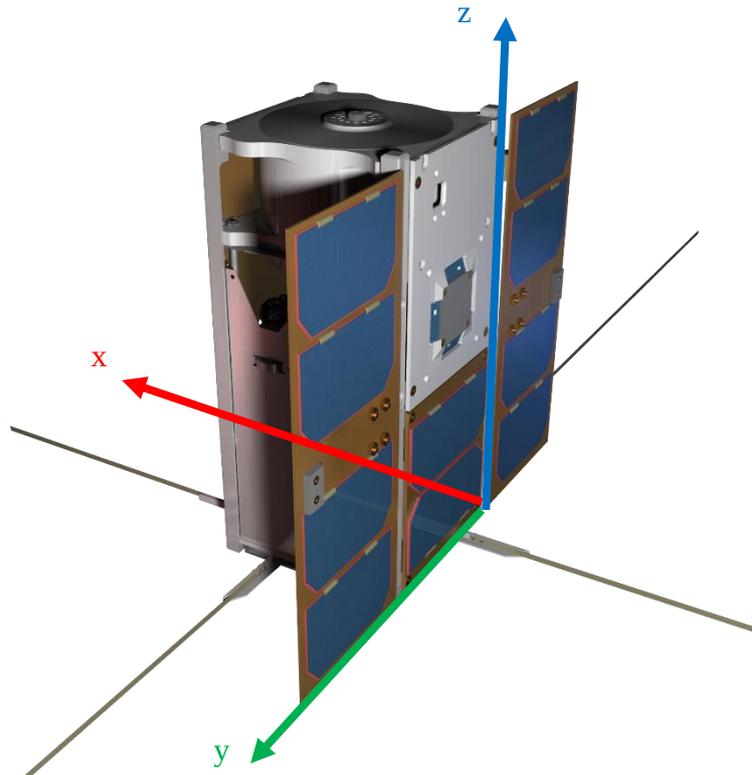


Figure 2-1 Body coordinate system of PW-Sat2

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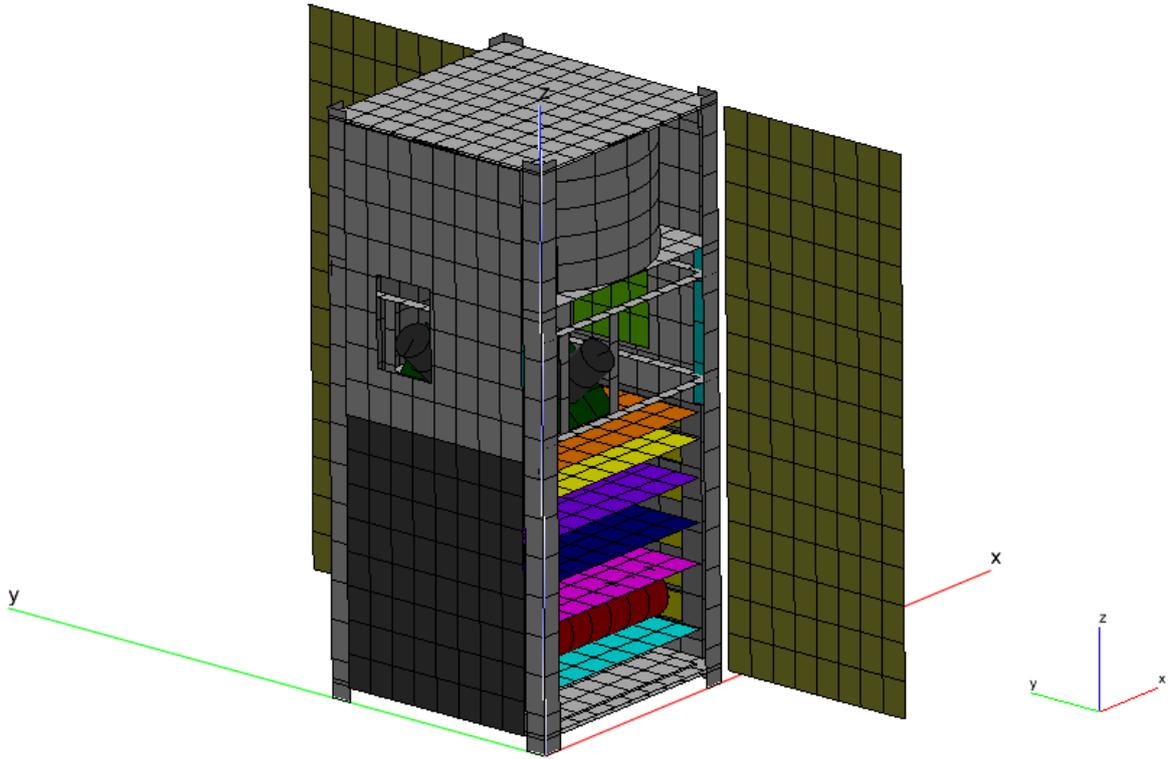


Figure 2-2 Coordinate system in ESATAN-TMS

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2.2 SATELLITE STRUCTURE AND CONFIGURATION

A general view of the configuration, with exposed internal structure and named components is shown below.

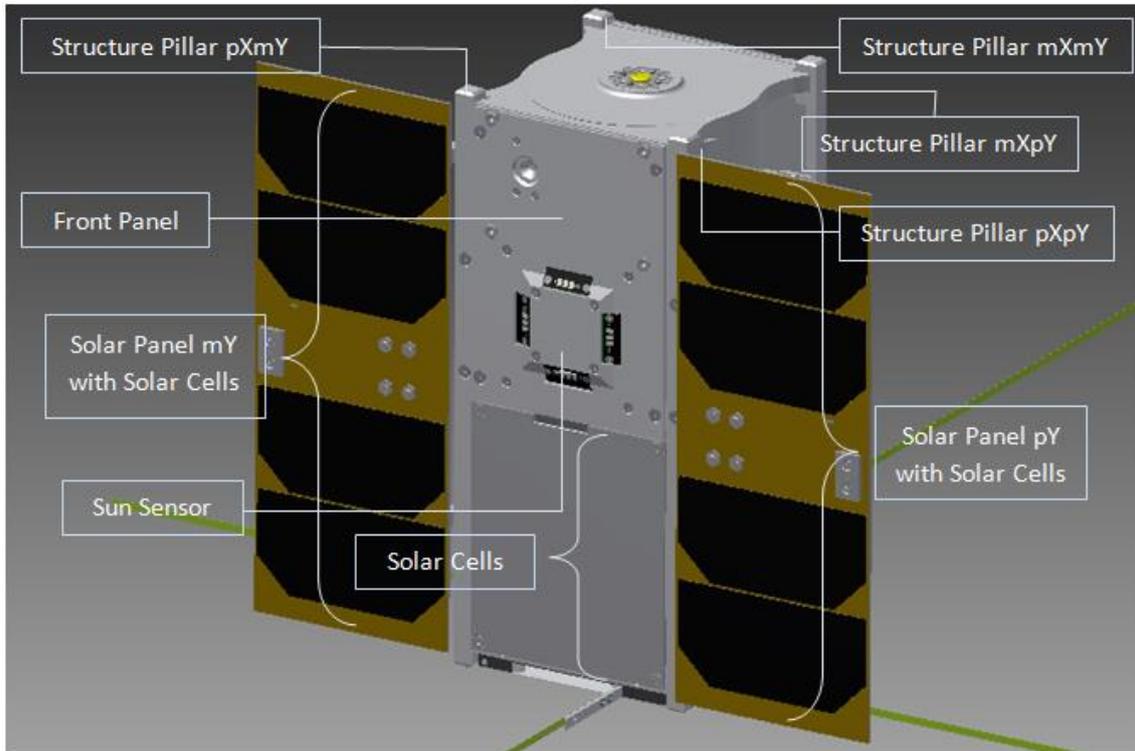


Figure 2-3 Front side

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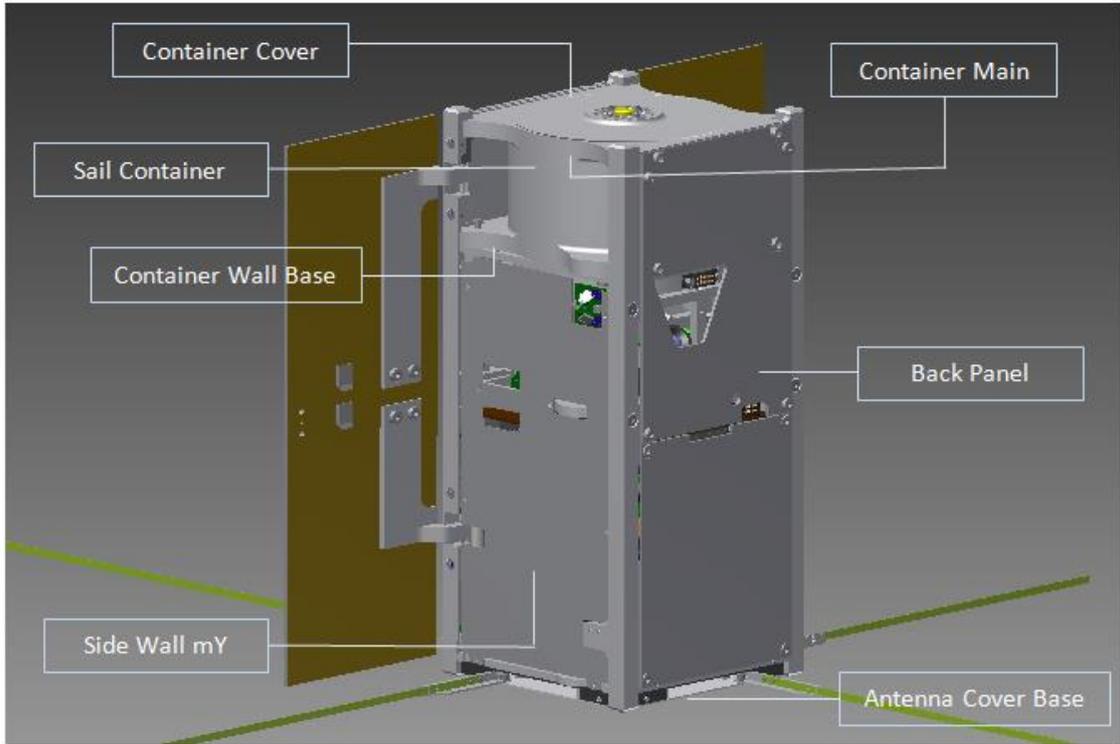


Figure 2-4 Rare side with the Side Wall mY

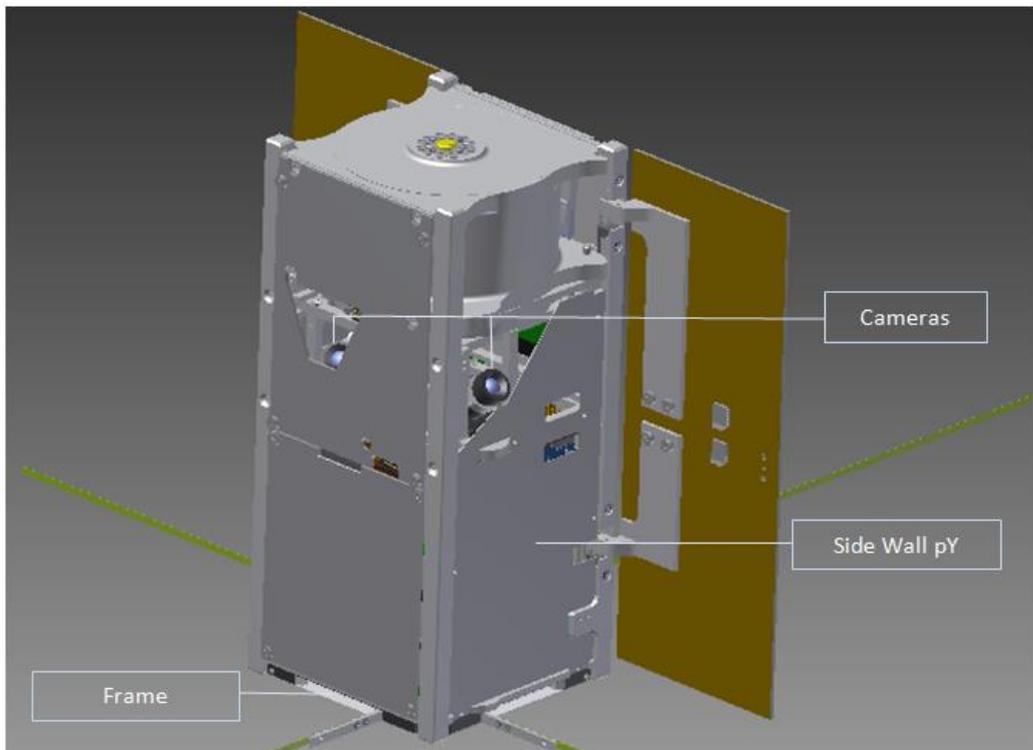


Figure 2-5 Rare side with the Side Wall pY

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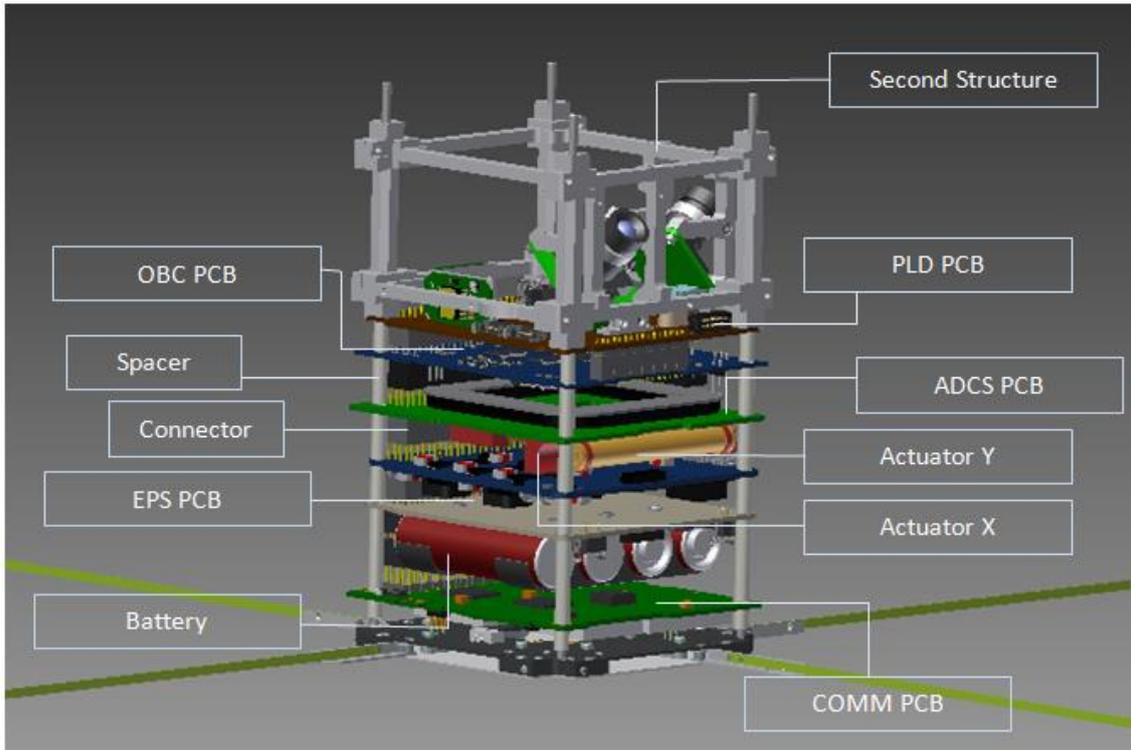


Figure 2-6 Components inside

Due to the complexity of the geometry, some elements had to be simplified in order to easily implement the geometry in ESATAN-TMS environment.

The front wall (FW) of the satellite has been divided into two parts where the upper is Front Panel and the lower in its entirety is Solar Cell FW. Similarly it has been done on the rear panel – Back Panel and Solar Cell Back Wall (BW).

It was assumed that the Sail Container is empty and radiatively inactive due to the sail insulative properties. For simplicity, it was assumed that the Container Main is the square with the circle cut in the middle. The shape of Container Wall Base was determined as the square.

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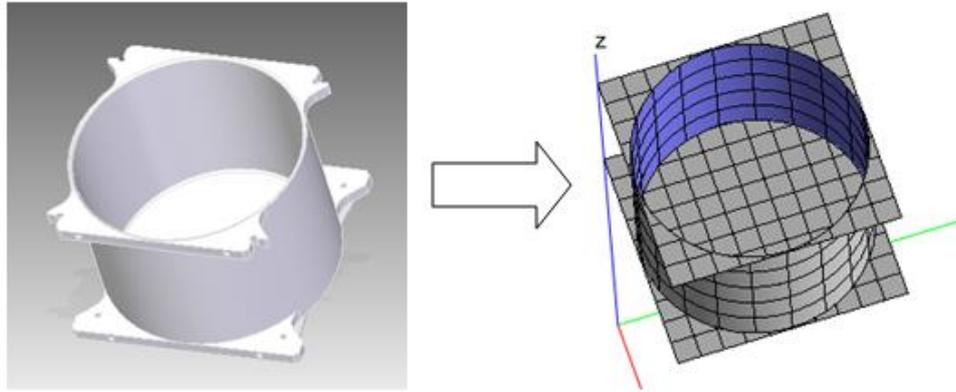


Figure 2-7 Sail Container simplification

Sun sensors were implemented parallel to the Front Wall, not tilted by 45deg as in CAD model (Figure 2-3), due to small influence of this change and simplicity of the geometric model.

Due to the very complex geometry of the antenna module, it was assumed as effective flat plate. Antenna straps were not included in the geometry due to their low radiative significance.

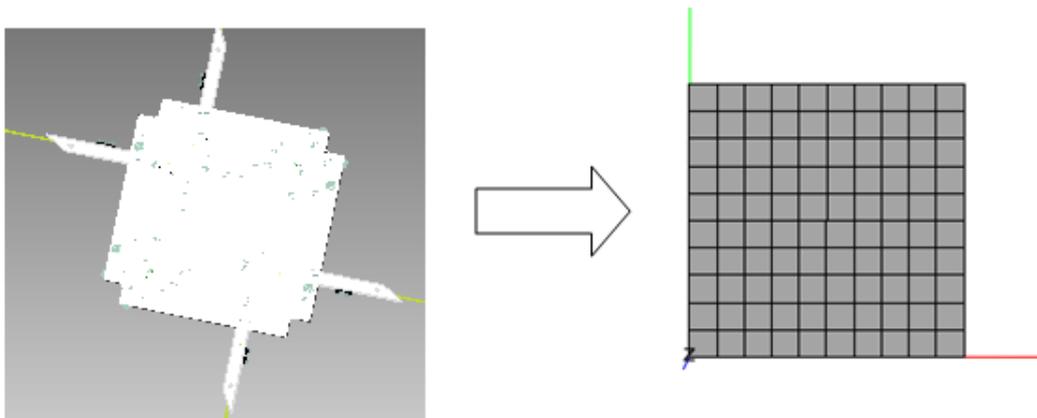


Figure 2-8 Antenna module simplification

In order to simplify the geometry and due to the marginal radiative impact, spacers have been not included in the geometrical model.

During Phase C the cameras were introduced in the geometric model of the satellite, and simplified to the cylinder and square plate, as shown in Figure 2-9. Cameras are held by additional structure called Second Structure.

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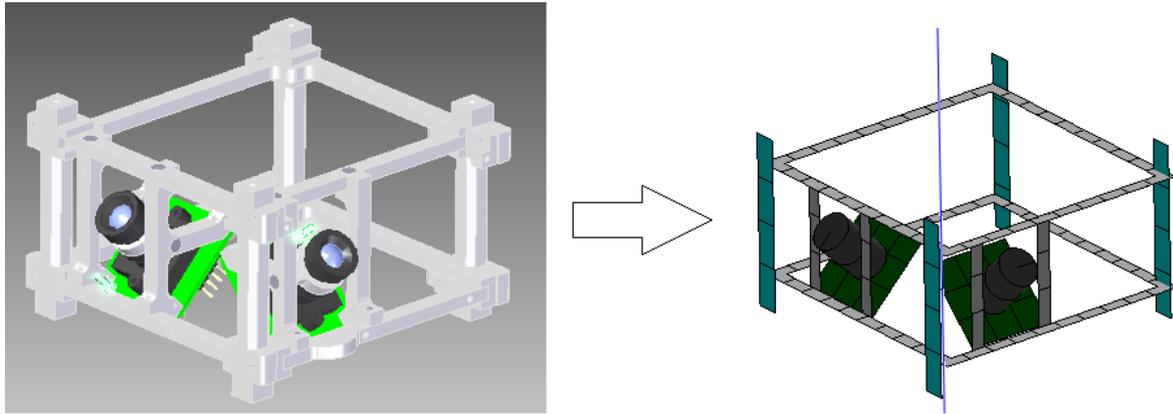


Figure 2-9 Cameras Second Structure module simplification

As a solution to high temperatures on batteries, the aluminium side walls were added to the geometric model. They were simplified as shown in Figure 2-10 and Figure 2-11 below.

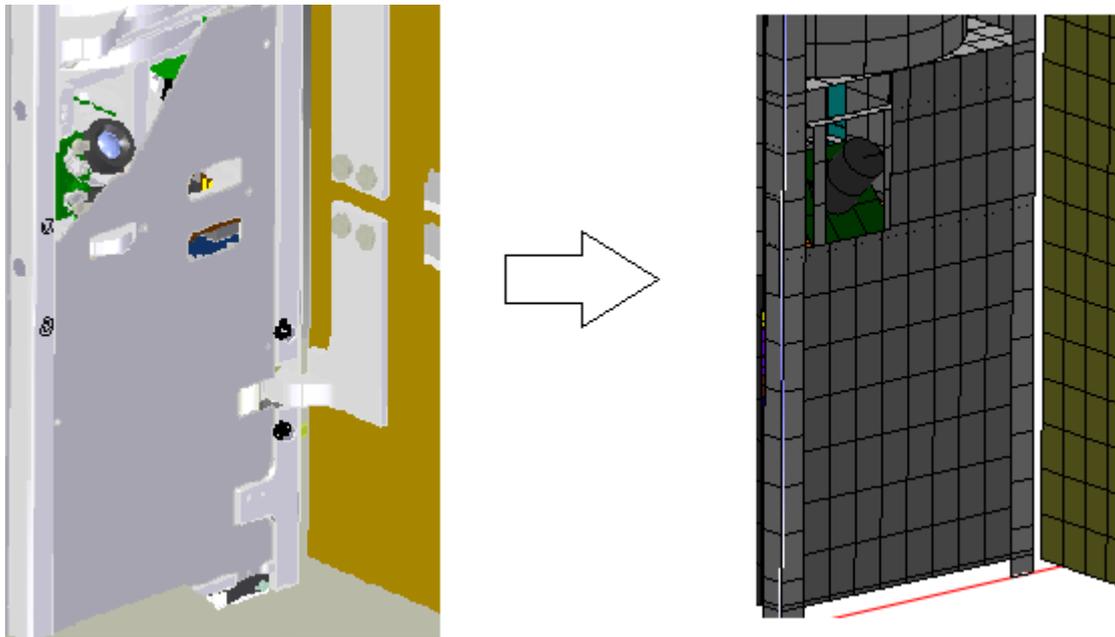


Figure 2-10 Side Wall (pY) simplification

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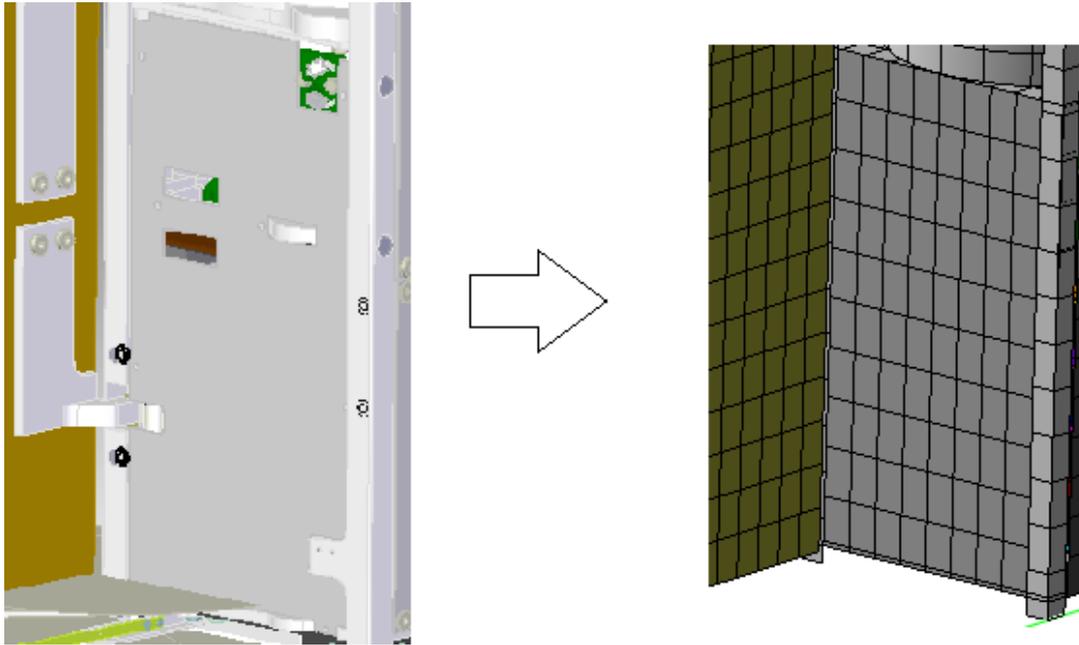


Figure 2-11 Side Wall (mY) simplification

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2.3 MATERIAL PROPERTIES

Thermal data of material properties used for every component.

Table 2-1 Material properties of components

| Component | Quantity | Material | Density [kg/m ³] | Specific heat [J/kg/K] | Conductivity [W/m/K] |
|-------------------------|----------|------------------------------|---------------------------------|---------------------------|-------------------------|
| Front panel | 1 | Aluminum 6061 | 2710 | 896 | 167 |
| Rear panel | 1 | Aluminum 6061 | 2710 | 896 | 167 |
| Side walls | 2 | Aluminium 6061 | 2710 | 896 | 167 |
| Frame | 1 | Aluminum 6061 | 2710 | 896 | 167 |
| Sail Container | 1 | Aluminum 6061 | 2710 | 896 | 167 |
| Support Rod | 4 | Stainless Steel | 8080 | 510 | 20 |
| Spacer | 24 | Aluminum 6061 | 2710 | 896 | 167 |
| Solar panel | 2 | Aluminium 6061 | 2710 | 896 | 167 |
| OBC PCB | 1 | FR-4 | 1850 | 1100 | 0.2 |
| ADCS PCB | 1 | FR-4 | 1850 | 1100 | 0.2 |
| Actuator ¹ | 2 | Ferrite/Copper | 5000 | 498 | 280 |
| Sun Sensor | 1 | Aluminum 6061 | 2710 | 896 | 167 |
| CAM1 ² | 1 | FR-4 | 1850 | 1100 | 0.2 |
| CAM2 ³ | 1 | FR-4 | 1850 | 1100 | 0.2 |
| PAYLOAD PCB | 1 | FR-4 | 1850 | 1100 | 0.2 |
| EPS PCB | 1 | FR-4 | 1850 | 1100 | 0.2 |
| Solar Cell ⁴ | 10 | GaAs | 572 | 310 | 59 |
| Batteries ⁵ | 4 | Li-ion | 1824 | 825 | 0.49 |
| Antenna ⁶ | 1 | Aluminum/FR-4 | 2400/1850 | 1030 | 57 |
| COMM PCB | 1 | FR-4 | 1850 | 1100 | 0.2 |
| Connector ⁷ | 6 | Polyester/Phosphor Bronze | 180 | 839 | 14.5 |
| Radiator | 1 | FEP/Aluminum | 0.333 | - | - |

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The following properties were calculated manually, those calculations are included below.

¹ Actuators are made of ferrite and copper parts. Based on the CAD model, it was determined that 70% of the total volume is copper and 30% is ferrite. According to Table 2-1, copper parameters are: $C_{Cu} = 390 \frac{J}{kg \times K}$, $\lambda_{Cu} = 400 \frac{W}{m \times K}$ and ferrite parameters are: $C_F = 750 \frac{J}{kg \times K}$, $\lambda_F = 0.003 \frac{W}{m \times K}$. On that basis the specific heat and conductivity of actuators were calculated as: $C = \frac{CCu \times 70\% + CF \times 30\%}{100\%} = 498 \frac{J}{kg \times K}$; $\lambda = \frac{\lambda_{Cu} \times 70\% + \lambda_F \times 30\%}{100} = 280 \frac{W}{m \times K}$.

^{2, 3} Cameras are mainly composed of FR-4 parts, but also PET and glass components. Due to the minor thermal impact and in order to simplify the calculations, it was assumed that the cameras are made of FR-4.

⁴ It was assumed that the solar cells are only made from Gallium arsenide.

⁵ Due to the lack of specification from the manufacturer, specific heat and conductivity were determined based on data from [1].

⁶ The antenna module is made of aluminum 6061 and FR-4 parts. Based on the CAD model, the aluminum parts occupy approximately 34% and Fr-4 parts 66% of the total volume. Module was simplified to the effective flat plate and effective specific heat and conductivity were calculated as:

$$C = \frac{CAI \times 34\% + CFR-4 \times 66\%}{100\%} = 1030 \frac{J}{kg \times K}; \lambda = \frac{\lambda_{AI} \times 34\% + \lambda_{FR-4} \times 66\%}{100\%} = 57 \frac{W}{m \times K}.$$

⁷ Due to the lack of data, it was assumed that black glass filled polyester accounts for 50% and phosphor bronze for 50% of total volume. Polyester properties are as following: $C_P = 1300 \frac{J}{kg \times K}$, $\lambda_P = 0.05 \frac{W}{m \times K}$; phosphor bronze properties: $C_B = 377 \frac{J}{kg \times K}$, $\lambda_B = 28.9 \frac{W}{m \times K}$. Effective specific heat and thermal conductivity were calculated as: $C = \frac{CP \times 50\% + CB \times 50\%}{100\%} = 839 \frac{J}{kg \times K}$; $\lambda = \frac{\lambda_P \times 50\% + \lambda_B \times 50\%}{100\%} = 14.5 \frac{W}{m \times K}$.

The bulk material properties that were used in ESATAN-TMS are shown below in the Figure 2-12 and Figure 2-13.

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Bulk Properties

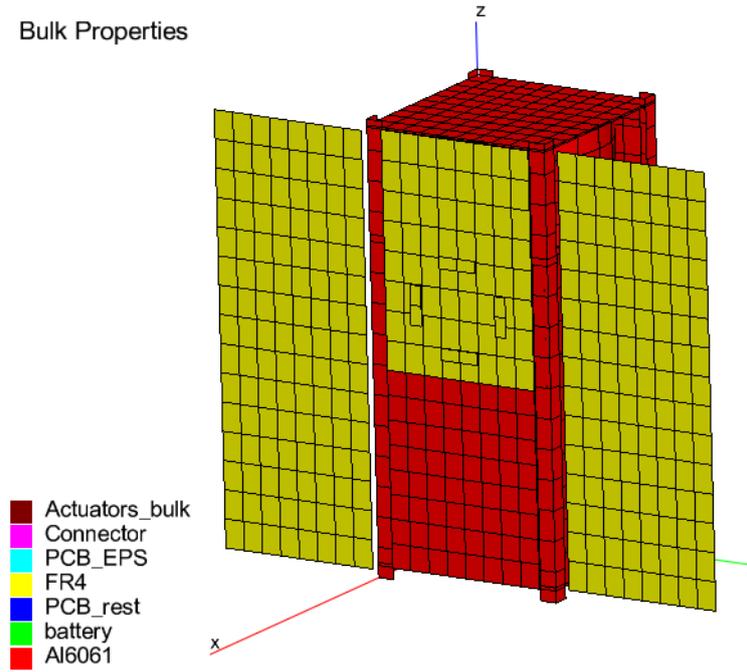


Figure 2-12 Bulk properties of components on the front side

Bulk Properties

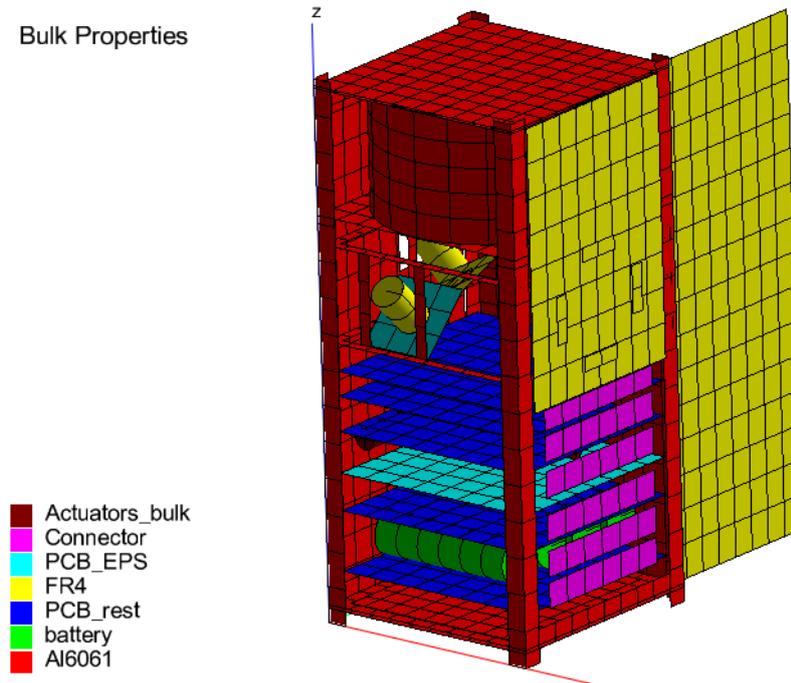


Figure 2-13 Bulk properties of components inside

| | | | |
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2.4 THERMO-OPTICAL PROPERTIES

Table 2-2 Optical properties of components

| Geometry name | Optical Coating | Emissivity | Absorptivity |
|---------------------|-----------------|------------|--------------|
| Solar panels | Aluminium | 0.07 | 0.879 |
| Front panel | Aluminium 6061 | 0.07 | 0.13 |
| Back panel | Aluminium 6061 | 0.07 | 0.07 |
| Side walls (pY, mY) | Aluminium 6061 | 0.07 | 0.07 |
| Container Cover | Aluminium 6061 | 0.07 | 0.07 |
| Structure Pillar | Aluminium 6061 | 0.07 | 0.07 |
| Second Structure | Aluminium 6061 | 0.07 | 0.07 |
| Antenna Cover Base | Aluminium 6061 | 0.07 | 0.07 |
| Solar Cell | GaAs | 0.85 | 0.91 |

To simplify the calculations, the Solar panels were treated as a mix of solar cells and Aluminium. The effective emissivity and absorptivity of panels surface have been calculated manually. Based on the CAD model it was measured that 72% of solar panel surface occupy solar cells and the rest is covered by aluminium. According to data [Datasheet_TCS_v2.2], the optical parameters of solar cells are: $\epsilon_{SC} = 0.85$; $\alpha_{SC}=0.91$, and the optical parameters of Aluminium are: $\epsilon_{FR-4} = 0.07$; $\alpha_{FR-4}=0.14$. The effective emissivity and absorptivity wa calculated as following: $\epsilon = \frac{\epsilon_{SC} \times 72\% + \epsilon_{(Al)} \times 28\%}{100\%} = 0.632$; $\alpha = \frac{\alpha_{SC} \times 72\% + \alpha_{(Al)} \times 28\%}{100\%} = 0.692$.

The optical properties for each component are shown in the Figure 2-14, Figure 2-15, Figure 2-16.

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Thermo-optical Properties

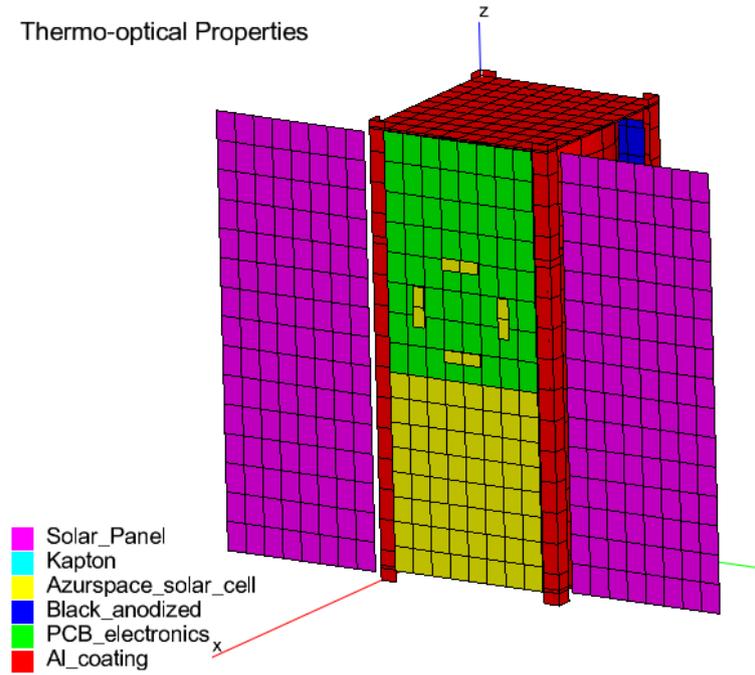


Figure 2-14 Thermo-optical properties of front side components

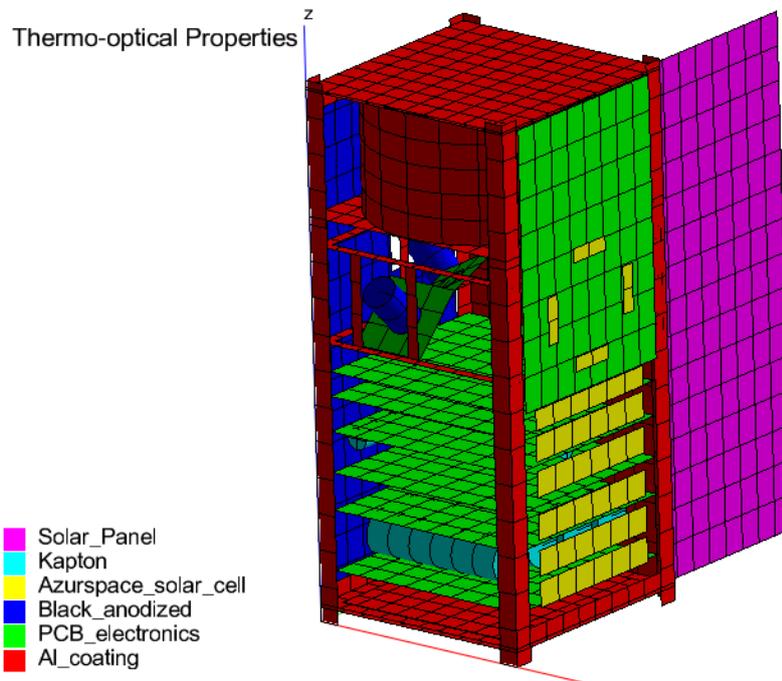


Figure 2-15 Thermo-optical properties of components inside

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Thermo-optical Properties

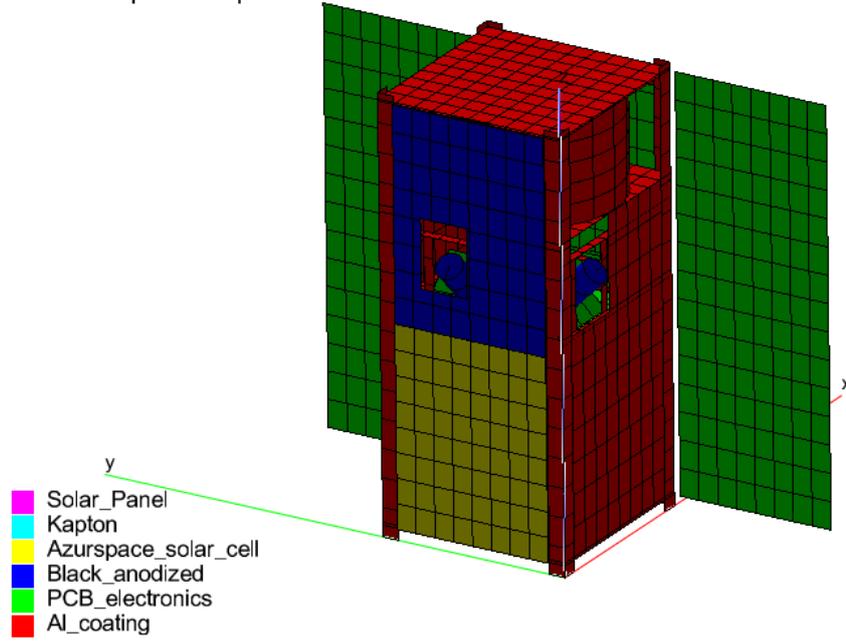


Figure 2-16 Thermo-optical properties of rear side components

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2.5 TEMPERATURE LIMITS

Applied temperature safety range +/- 5°C (Acceptance limit). Table containing max and min qualification (design) limit and acceptance limit for each component.

Table 2-3 Temperature limits of components

| Component | Min qualification limit (°C) | Min acceptance limit (°C) | Max acceptance limit (°C) | Max qualification limit (°C) |
|----------------|------------------------------|---------------------------|---------------------------|------------------------------|
| Front panel | -90 | -85 | 105 | 110 |
| Rear panel | -90 | -85 | 105 | 110 |
| Frame | -90 | -85 | 105 | 110 |
| Sail Container | -90 | -85 | 105 | 110 |
| Support Rod | -100 | -95 | 995 | 1000 |
| Spacer | -90 | -85 | 105 | 110 |
| Solar panel | -150 | -145 | 105 | 110 |
| OBC PCB | -40 | -35 | 80 | 85 |
| ADCS PCB | -40 | -35 | 65 | 70 |
| Actuator | -35 | -30 | 70 | 75 |
| Sun Sensor | -50 | -45 | 75 | 80 |
| CAM1 | -35 | -30 | 85 | 90 |
| CAM2 | -35 | -30 | 85 | 90 |
| PAYLOAD PCB | -30 | -25 | 55 | 60 |
| EPS PCB | -30 | -25 | 55 | 60 |
| Solar Cell | -40 | -35 | 115 | 120 |
| Battery | 0 | 5 | 35 | 40 |
| Antenna | -30 | -25 | 65 | 70 |
| COMM PCB | -30 | -25 | 55 | 60 |
| Connector | -65 | -60 | 120 | 125 |
| Radiator | -60 | -55 | 115 | 120 |

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2.6 CONDUCTIVE INTERFACES

Due to assumptions made in the geometric model, thermal couplings between simplified elements of satellite had to be calculated manually.

A conductance was calculated by assuming that the heat flows one-dimensionally from one section to the next parallel to a line between the nodes. With this assumption, a conductance - called GL - is given by the formula

$$GL = \frac{kA}{x}$$

where k is thermal conductivity of the material, A is cross-sectional area of the node and x the distance between nodes.

Only a small fraction of the nominal surface area is actually in contact because of the curvatures and roughness of the contacting surfaces. This limited contact area causes a thermal contact resistance R . Thermal contact conductance $h = \frac{1}{R}$ is taken into consideration, while calculating parallel thermal couplings between nodes, according to the formula

$$\frac{1}{GL} = \frac{1}{GL_{contact}} + \frac{1}{GL_1}$$

where $GL_{contact} = hA$

2.6.1 THERMAL COUPLINGS BETWEEN SPACERS, SUPPORT RODS AND PCB

The PLD_PCB, OBC_PCB, ADCS_PCB, EPS_PCB, ACCU_PCB, COMM_PCB and frame are connected by 4 support rods and 24 spacers symmetrically in pXpY, pXmY, mXpY and mXmY corners (Figure 2-5).

Each PCB is connected with a set of four spacers, where each one is thermally divided into half – due to the thermal modelling philosophy – resulting in 8 GLs between every PCB. Spacer conductivity is 167 W/m²/K for each element and the connection area per node is 2.31221E-05 m². Distance between nodes from PLD_PCB to frame vary depending on the distance between PCBs and are: 0.005, 0.005, 0.006, 0.006, 0.0075, 0.0075, 0.00585, 0.00585, 0.013, 0.013, 0.006, 0.006m respectively.

Thermal couplings were calculated as following:

$$GL_{spacer11} = \frac{167 * 2.31221 * 10^{-5}}{0.005} = 0,772278872 \frac{W}{K}$$

$$GL_{spacer12} = \frac{167 * 2.31221 * 10^{-5}}{0.005} = 0,772278872 \frac{W}{K}$$

$$GL_{spacer21} = \frac{167 * 2.31221 * 10^{-5}}{0.006} = 0,643565727 \frac{W}{K}$$

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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$$GL_{spacer2_2} = \frac{167 * 2.31221 * 10^{-5}}{0.006} = 0,643565727 \frac{W}{K}$$

$$GL_{spacer3_1} = \frac{167 * 2.31221 * 10^{-5}}{0.0075} = 0,514852582 \frac{W}{K}$$

$$GL_{spacer3_2} = \frac{167 * 2.31221 * 10^{-5}}{0.0075} = 0,514852582 \frac{W}{K}$$

$$GL_{spacer4_1} = \frac{167 * 2.31221 * 10^{-5}}{0.00585} = 0,6600674126 \frac{W}{K}$$

$$GL_{spacer4_2} = \frac{167 * 2.31221 * 10^{-5}}{0.00585} = 0,660067412 \frac{W}{K}$$

$$GL_{spacer5_1} = \frac{167 * 2.31221 * 10^{-5}}{0.013} = 0,297030336 \frac{W}{K}$$

$$GL_{spacer5_2} = \frac{167 * 2.31221 * 10^{-5}}{0.013} = 0,297030336 \frac{W}{K}$$

$$GL_{spacer6_1} = \frac{167 * 2.31221 * 10^{-5}}{0.006} = 0,643565727 \frac{W}{K}$$

$$GL_{spacer6_2} = \frac{167 * 2.31221 * 10^{-5}}{0.006} = 0,643565727 \frac{W}{K}$$

Support rod conductivity is 20 W/m²/K and the cross-sectional area is equal to 7.06858E-06m². Distance between nodes from PLD_PCB to frame are: 0.005, 0.005, 0.006, 0.006, 0.0075, 0.0075, 0.00585, 0.00585, 0.013, 0.013, 0.006, 0.006m respectively.

Conductance through support rod is calculated:

$$GL_{rod11} = \frac{20 * 7.06858 * 10^{-6}}{0.005} = \frac{W}{K}$$

$$GL_{rod12} = \frac{20 * 7.06858 * 10^{-6}}{0.005} = 0,028274334 \frac{W}{K}$$

$$GL_{rod21} = \frac{20 * 7.06858 * 10^{-6}}{0.006} = 0,235619449 \frac{W}{K}$$

$$GL_{rod22} = \frac{20 * 7.06858 * 10^{-6}}{0.006} = 0,235619449 \frac{W}{K}$$

$$GL_{rod31} = \frac{20 * 7.06858 * 10^{-6}}{0.0075} = 0,018849556 \frac{W}{K}$$

$$GL_{rod32} = \frac{20 * 7.06858 * 10^{-6}}{0.0075} = 0,018849556 \frac{W}{K}$$

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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$$GL_{rod41} = \frac{20 * 7.06858 * 10^{-6}}{0.00585} = 0,024166097 \frac{W}{K}$$

$$GL_{rod42} = \frac{20 * 7.06858 * 10^{-6}}{0.00585} = 0,024166097 \frac{W}{K}$$

$$GL_{rod51} = \frac{20 * 7.06858 * 10^{-6}}{0.013} = 0,010874744 \frac{W}{K}$$

$$GL_{rod52} = \frac{20 * 7.06858 * 10^{-6}}{0.013} = 0,010874744 \frac{W}{K}$$

$$GL_{rod61} = \frac{20 * 7.06858 * 10^{-6}}{0.006} = 0,023561945 \frac{W}{K}$$

$$GL_{rod62} = \frac{20 * 7.06858 * 10^{-6}}{0.006} = 0,023561945 \frac{W}{K}$$

Thermal contact conductance between stainless steel and Aluminium 6061 was assumed to be 1000 W/m²/K [2]. Area of contact is 9.42478E-06m².

Thermal contact conductance was calculated:

$$GL_{contact} = 1000 * 9.42478 * 10^{-6} = 9.42478 * 10^{-3} \frac{W}{K}$$

Thermal couplings were calculated for given formula:

$$GL_{cont} = \left(\frac{1}{GL_{rod}} + \frac{1}{GL_{contact1}} \right)^{-1}$$

Thermal couplings between support rods and spacers are given by formula:

$$GL_{rod_spacer} = GL_{cont} + GL_{rod}$$

Thermal contact conductance between PCBs and support rod is assumed to be 1000 W/m²/K, according to RD-2. Area of contact is equal to 2.31221E-05m².

Thermal contact conductance was calculated:

$$GL_{contact2} = 1000 * 2.31221 * 10^{-5} = 0.0231221 \frac{W}{K}$$

Finally, thermal coupling between PCB and support rod is calculated by formula:

$$GL = \left(\frac{1}{GL_{rod_spacer}} + \frac{1}{GL_{contact2}} \right)^{-1}$$

Results of final thermal couplings between each PCB and their respective support rod are presented in Table 2-4.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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Table 2-4 Total GL values

| From | To | Total GL value [W/K] per rod |
|----------|----------|---------------------------------|
| PLD_PCB | Spacer1 | 0.02245589 |
| Spacer1 | OBC_PCB | 0.02245589 |
| OBC_PCB | Spacer2 | 0.023039462 |
| Spacer2 | ADCS_PCB | 0.023039462 |
| ADCS_PCB | Spacer3 | 0.022139815 |
| Spacer3 | EPS_PCB | 0.022139815 |
| EPS_PCB | Spacer4 | 0.022347261 |
| Spacer4 | ACCU_PCB | 0.022347261 |
| ACCU_PCB | Spacer5 | 0.021478121 |
| Spacer5 | COMM_PCB | 0.021478121 |
| COMM_PCB | Spacer6 | 0.022328218 |
| Spacer6 | Frame | 0.022328218 |

2.6.2 THERMAL COUPLING BETWEEN SOLAR PANELS AND STRUCTURE

Heat exchange between solar panels and the structure takes place through 4 hinges. Due to the very low contact area, long thermal distance between panel and the structure and no metal-to-metal contact, thermal couplings are considered negligible.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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| | Phase C | | |

3 ENVIRONMENT DESCRIPTION & ORBIT DEFINITION

This chapter defines environment setup used for analysis and the most probable Sun-Synchronous orbit, based on the selected launch provider. For the initial case (ejection from the rocket until nominal sun pointing) orbit properties are the same, but different behaviour of the satellite.

3.1 ENVIRONMENT SETUP

Environment Setup is defined by standard parameters generated by ESATAN. Data are presented in a-figure below. When it comes to albedo reflectance, the variation in the Earth’s albedo is dependent on latitude, cloud cover, ice fields and other factors. Therefore it was assumed that the value of the albedo is higher at the poles – approximately 0.8 at the angle of 20° between the point of modified albedo and the pole - and reduced to 0.3 for the rest of the orbit. For the initial cases after the ejection from rocket the value of albedo is assumed at the average of 0.5.

| | |
|----------------------------|-------------------------------------|
| ☐ Sun/Planet System | |
| Orbit Centre | PLANET |
| Planet Radius | 6,378,140 |
| Gravitational Acceleration | 9.80655 |
| Sun Planet Distance | 149,597,870,000 |
| Solar Declination | 0 |
| Sun's Right Ascension | 0 |
| Orbital Precession | 0 |
| Sun Radius | 695,800,000 |
| ☐ Sun Specific | |
| Sun Temperature | 5,770 |
| Solar Constant Override | 0 |
| Sun Rays | Parallel Rays |
| Sun Distance Override | 0.0 |
| ☐ Planet Specific | |
| Albedo Reflectance | 0.3 |
| Infra-Red Emissivity | 1 |
| Temperature Method | UNIFORM |
| Planet Temperature | 288 |
| Temperature Distributi... | Not Defined |
| Interpolate Temperature | <input checked="" type="checkbox"/> |
| Latitude Steps | 37 |
| Longitude Steps | 36 |
| Solar Absorbivity | 1 |
| Night-Side Temperatur... | |

Figure 17 Environment setup

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

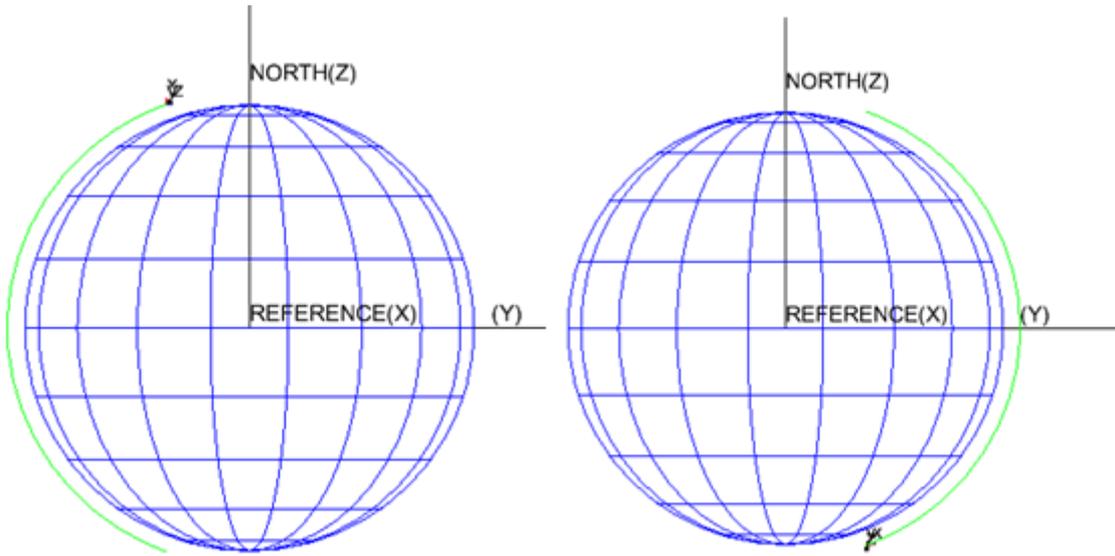


Figure 18 Parts of orbit with albedo 0.3

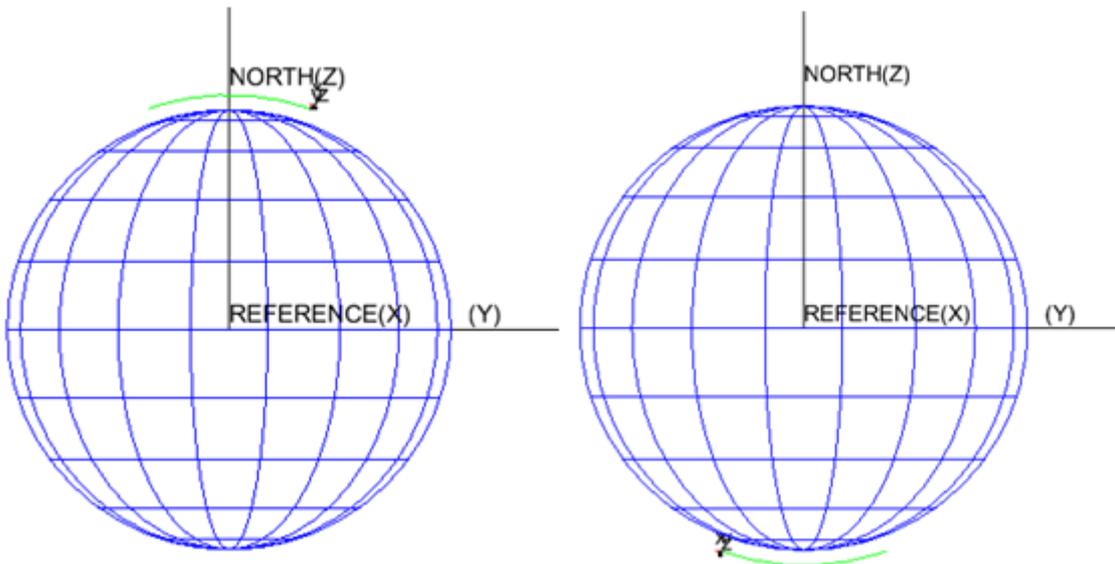


Figure 19 Parts of orbit with albedo 0.8

3.2 ORBIT DEFINITION

All of the cases are defined on Sun-Synchronous orbit, with altitude of 500 km. Inclination is set to 97.89 degrees. For full orbit definition refer to Figure 3-20.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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| | |
|---------------------------|--------------------------|
| [-] Ellipse | |
| Altitude of Apogee | 500,000 |
| Altitude of Perigee | 500,000 |
| Inclination | 97.89 |
| Right Ascension | 0 |
| Argument of Periapsis | 0 |
| [-] Arc | |
| Initial True Anomaly | 0 |
| Final True Anomaly | 360 |
| [-] Positions | |
| Angle Gap | 45 |
| Number of Positions | 8 |
| True Anomalies Vector | |
| Eclipse Entry Exit Points | <input type="checkbox"/> |
| Eclipse Offset | 0.5 |
| [-] Ephemeris | |
| Type | Position & Velocity |
| Longitude | 0 |
| Latitude | 0 |
| Azimuth | 90 |
| Matrix | Not Defined |

Figure 3-20 Orbit definition

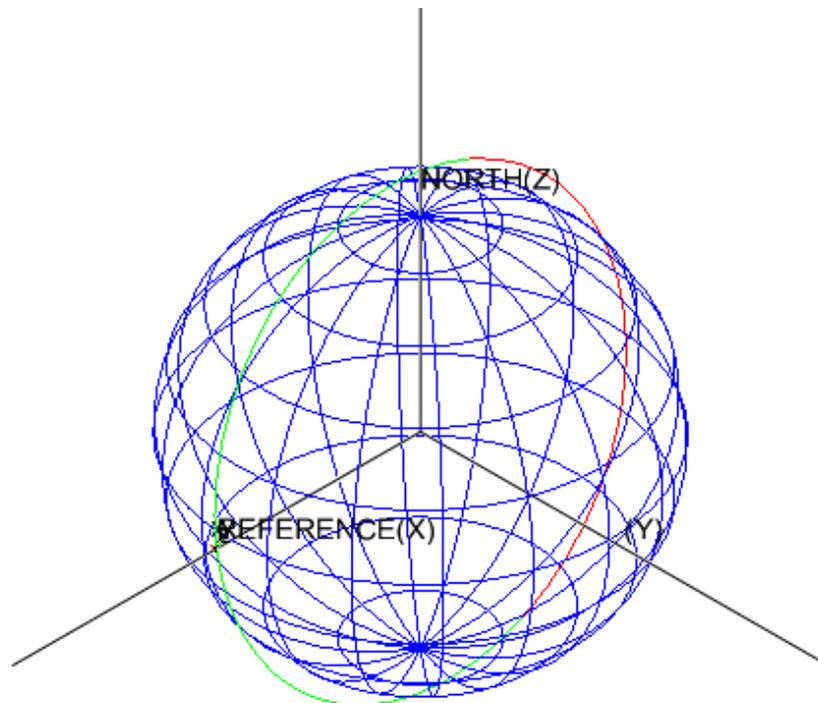


Figure 3-21 Orbit visualisation

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

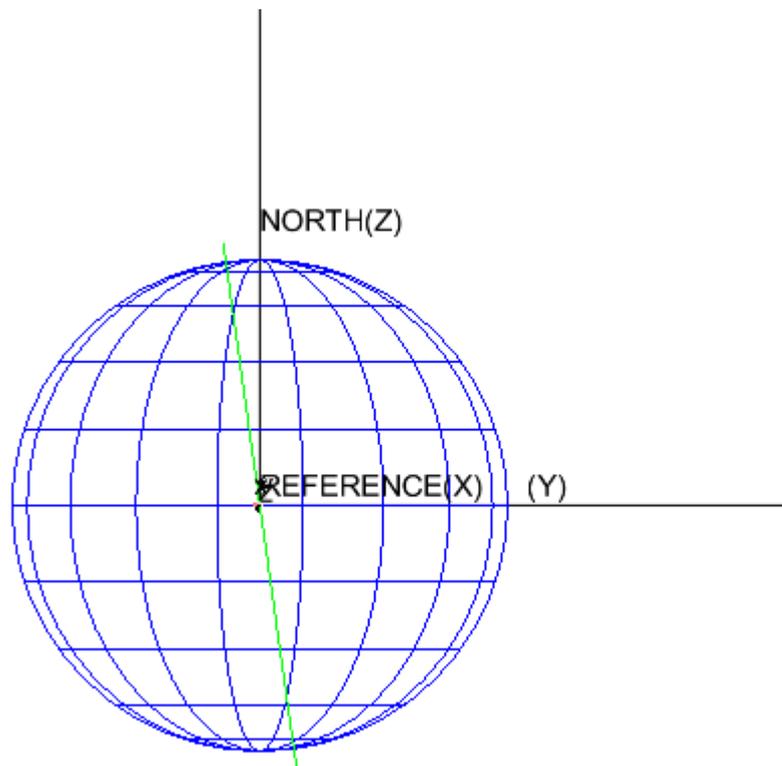


Figure 3-22 Orbit visualisation, view from +X

3.3 NOMINAL SUNPOINTING.

In Nominal Sunpointing case, front wall faces the Sun over the entire orbit. This case is performed by setting model's Primary Pointing Vector to be aligned to direction of the Sun. The Primary Pointing Vector is set to the +X axis of the Model Coordinate System (MCS) and the Pointing Direction to TRUE_SUN with General Direction set to the +X axis of the Inertial Coordinate System. The Secondary Pointing Vector is set to the +Y axis and the Secondary Pointing Direction to the VELOCITY to define the orientation of the spacecraft on its orbit. Omega rotation rate determines rotation about the Z axis of the MCS and its value is set as terminal value occurring in detumbling. Parameters are shown in Figure 3-22.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

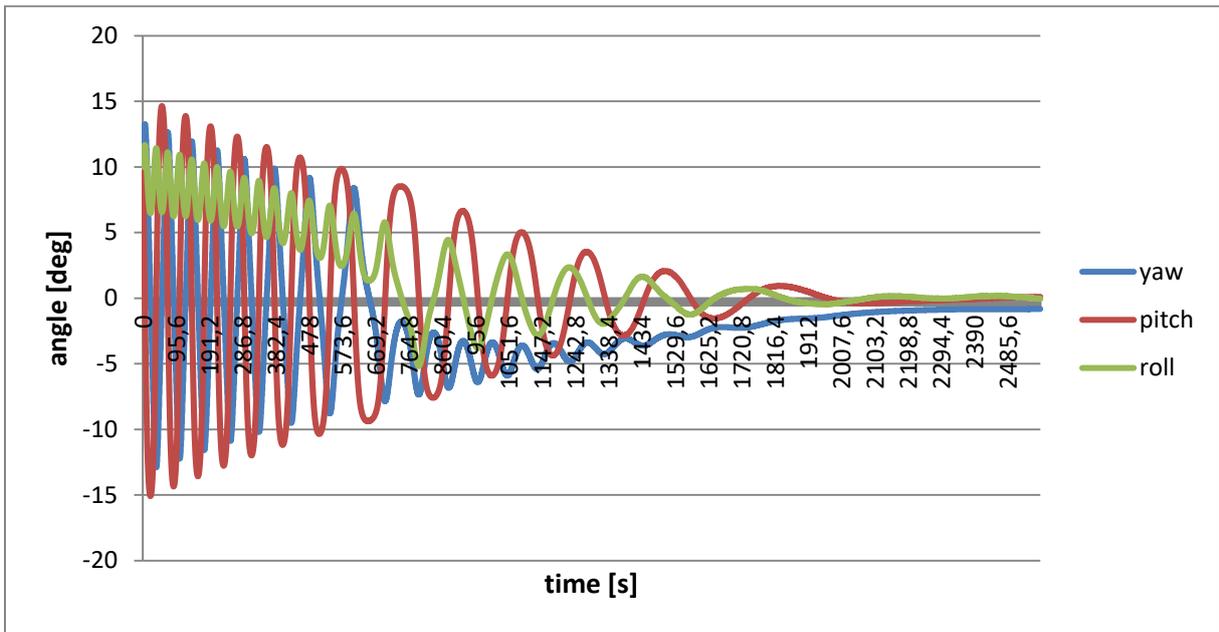
| | |
|------------------------|--------------------------|
| ☐ Primary Pointing | |
| Pointing Vector | [1.0, 0.0, 0.0] |
| Pointing Direction | TRUE_SUN |
| General Direction | [1.0, 0.0, 0.0] |
| ☐ Secondary Pointing | |
| Pointing Vector | [0.0, 1.0, 0.0] |
| Pointing Direction | VELOCITY |
| General Direction | [0.0, -1.0, 0.0] |
| ☐ LOCS Orientation | |
| Orientation | PLANET_ORIENTED |
| ☐ User Defined Mov... | |
| Phi | 0.0 |
| Psi | 0.0 |
| Omega | 0.0 |
| Phi Rotation Rate | 0.0 |
| Psi Rotation Rate | 0.0 |
| Omega Rotation Rate | 5.0 |
| Application Order | phi, psi, omega |
| ☐ Spacecraft Movem... | |
| Spin | <input type="checkbox"/> |
| Spin Axis | Not Defined |
| Spin Positions | 4.0 |
| Initial Angular Offset | 0.0 |
| Rotation Rate | 0.0 |

Figure 3-23 Sunpointing properties

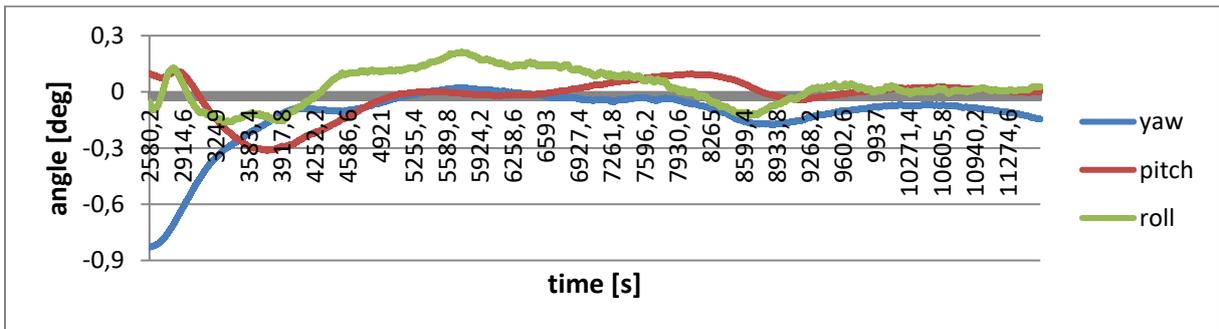
| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

3.4 DETUMBLING

Detumbling is the process of stabilizing the rotation of the satellite after orbital insertion. In order to simplify analyses in ESATAN, this case is defined as two separate radiative cases - named Detumbling and Sunpointing - where first determines rotation after orbital insertion and second the process of facing the Front Wall to the Sun direction. Parameters of Detumbling and Sunpointing radiative cases are determined by yaw, pitch and roll angles, as shown in graphs.



Graph 3-1 Detumbling, first 2580 seconds



Graph 3-2 Detumbling, from 2580.2 to 11608 second



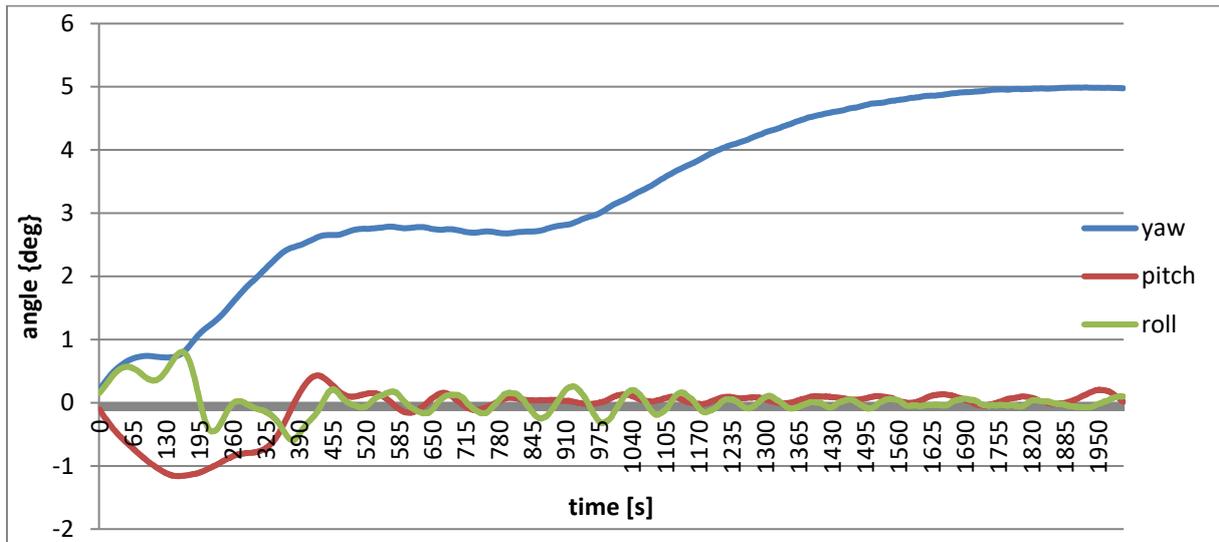
PW-Sat2

2016-11-30

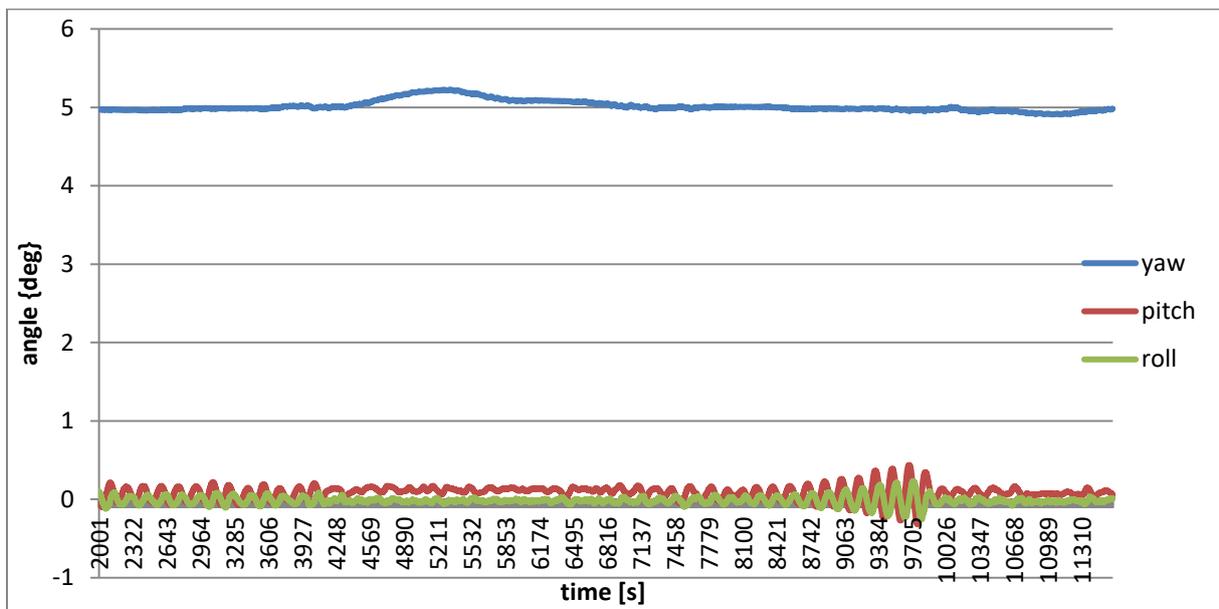
Phase C

Critical Design Review

Thermal Control System



Graph 3-3 Sunpointing, first 2000 seconds



Graph 3-4 Sunpointing, from 2001 to 11608 second

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

3.5 RANDOM POINTING

Random Pointing is the radiative case of ADCS failure, causing the inability to slow down satellite rotation and start Sun pointing process. In this case, the satellite does not follow any vectors, but constantly rotates around its three axes with the speed of 2 deg/s.

| | |
|---|--------------------------|
| <input type="checkbox"/> Primary Pointing | |
| Pointing Vector | [0.0, 1.0, 0.0] |
| Pointing Direction | GENERAL |
| General Direction | [1.0, 0.0, 0.0] |
| <input type="checkbox"/> Secondary Pointing | |
| Pointing Vector | [1.0, 0.0, 0.0] |
| Pointing Direction | GENERAL |
| General Direction | [0.0, 0.0, 1.0] |
| <input type="checkbox"/> LOCS Orientation | |
| Orientation | PLANET_ORIENTED |
| <input type="checkbox"/> User Defined Move... | |
| Phi | 180.0 |
| Psi | 180.0 |
| Omega | 180.0 |
| Phi Rotation Rate | 2 |
| Psi Rotation Rate | 2 |
| Omega Rotation Rate | 2 |
| Application Order | phi, psi, omega |
| <input type="checkbox"/> Spacecraft Moveme... | |
| Spin | <input type="checkbox"/> |
| Spin Axis | Not Defined |
| Spin Positions | 4 |
| Initial Angular Offset | 0 |
| Rotation Rate | 0 |

Figure 3-24 Random pointing properties

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

4 THERMAL CASES DEFINITION

Multiple thermal analyses were performed to check the viability of different possible situations. Mission analysis allowed to distinguish three specific modes, which were likely to be exposed to extreme temperatures, differing in the amount of heat generated, duration and location on orbit. Analysis were also conducted for most common case - Nominal Sun Pointing.

Table 4-1 Thermal cases

| Analysis case | Radiative case |
|---------------------|--------------------------|
| Nominal Sunpointing | Nominal Sunpointing |
| ADCS failure | Random Pointing |
| Detumbling | Detumbling |
| Sunpointing | Sunpointing (Detumbling) |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
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| | Phase C | | |

4.1 NOMINAL SUNPOINTING

Nominal Sun Pointing case defines thermal case in which the satellite is fixed in the Sun pointing position. Most instruments are working, generating 3.779W of heat in total. This is the most probable and longest case, therefore it is considered in this paper.

Table 4-2 Nominal Sunpointing - heat generation

| Nominal Sunpointing | | | |
|-------------------------------------|-----------|----------|---------------------------|
| Radiative case: Nominal Sunpointing | | | |
| System / Instrument | Unit | Quantity | Total heat generation [W] |
| OBC | PCB | 1 | 0.5 |
| ADCS | PCB | 1 | 0.133 |
| | Actuators | 2 | 0.033 |
| PAYLOAD | SunS | 2 | 0.25 |
| | CAM1 | 1 | 0 |
| | CAM2 | 1 | 0 |
| | PCB | 1 | 0.5 |
| EPS | PCB | 1 | 1.6 |
| | Batteries | 4 | 0.02 |
| COMM | PCB | 1 | 0.4 |
| SUM: | All | 15 | 3.779 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

4.2 ADCS FAILURE

ADCS failure case position of satellite on the orbit is defined by Random Pointing radiative case. Onboard instruments operation is limited, causing lower heat generation.

Table 4-3 Random Pointing PS - heat generation

| ADCS failure | | | |
|---------------------------------|-----------|----------|---------------------------|
| Radiative case: Random Pointing | | | |
| System / Instrument | Unit | Quantity | Total heat generation [W] |
| OBC | PCB | 1 | 0.5 |
| ADCS | PCB | 1 | 0 |
| | Actuators | 2 | 0 |
| PAYLOAD | SunS | 2 | 0 |
| | CAM1 | 1 | 0 |
| | CAM2 | 1 | 0 |
| | PCB | 1 | 0 |
| EPS | PCB | 1 | 0.6 |
| | Batteries | 4 | 0.01 |
| COMM | PCB | 1 | 0.4 |
| SUM: | All | 15 | 1.54 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

4.3 DETUMBLING

Due to the satellite rotation in detumbling case, it is possible that either hot or cold case may occur, depending on the orientation and rotation speed. Detumbling process is expected to last for about one orbit cycle.

Table 4-4 Detumbling - heat generation

| Detumbling | | | |
|----------------------------|-----------|----------|---------------------------|
| Radiative Case: Detumbling | | | |
| System / Instrument | Unit | Quantity | Total heat generation [W] |
| OBC | PCB | 1 | 0.5 |
| ADCS | PCB | 1 | 0.6 |
| | Actuators | 2 | 0.4 |
| PAYLOAD | SunS | 2 | 0 |
| | CAM1 | 1 | 0 |
| | CAM2 | 1 | 0 |
| | PCB | 1 | 0 |
| EPS | PCB | 1 | 0.6 |
| | Batteries | 4 | 0.01 |
| COMM | PCB | 1 | 0.4 |
| SUM: | All | 15 | 3.34 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

4.1 SUNPOINTING

Sunpointing analysis case occurs right after Detumbling. Heat generation is the same as in the Detumbling analysis case. Initial temperature of each node is set as temperature of the last time step of the Detumbling.

Table 4-5 Sunpointing - heat generation

| Sunpointing | | | |
|-----------------------------|-----------|----------|---------------------------|
| Radiative Case: Sunpointing | | | |
| System / Instrument | Unit | Quantity | Total heat generation [W] |
| OBC | PCB | 1 | 0.5 |
| ADCS | PCB | 1 | 0.6 |
| | Actuators | 2 | 0.4 |
| PAYLOAD | SunS | 2 | 0 |
| | CAM1 | 1 | 0 |
| | CAM2 | 1 | 0 |
| | PCB | 1 | 0 |
| EPS | PCB | 1 | 0.6 |
| | Batteries | 4 | 0.01 |
| COMM | PCB | 1 | 0.4 |
| SUM: | All | 15 | 3.34 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

5 RESULTS

The following chapter presents the results of thermal analysis of the satellite, performed using ESATAN-TMS software. Each set of results is divided into four cases, described in chapter 4. Separate analyses were performed for geometric model of the satellite with closed solar panels, in case of solar panels opening system failure.

For each case, the following set of results is presented: graph of temperature fluctuations over the orbit at solar panels, maximal and minimal temperature obtained at components and their limits.

Minimal and maximal temperature limits (respectively: LoLo and HiHi) are stated based on specification provided by component producer or material properties. 'Lo' and 'Hi' temperature limits are determined by adding 10°C of safety margin to lowest limit and reducing higher limit by 10°C. 5°C uncertainty was taken into consideration as a margin of error.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

5.1 OPENED SOLAR PANELS

5.1.1 NOMINAL SUNPOINTING RESULTS

This subchapter contains results of a Nominal Sunpointing (see chapter 4.1), which is the most probable case that will result.

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

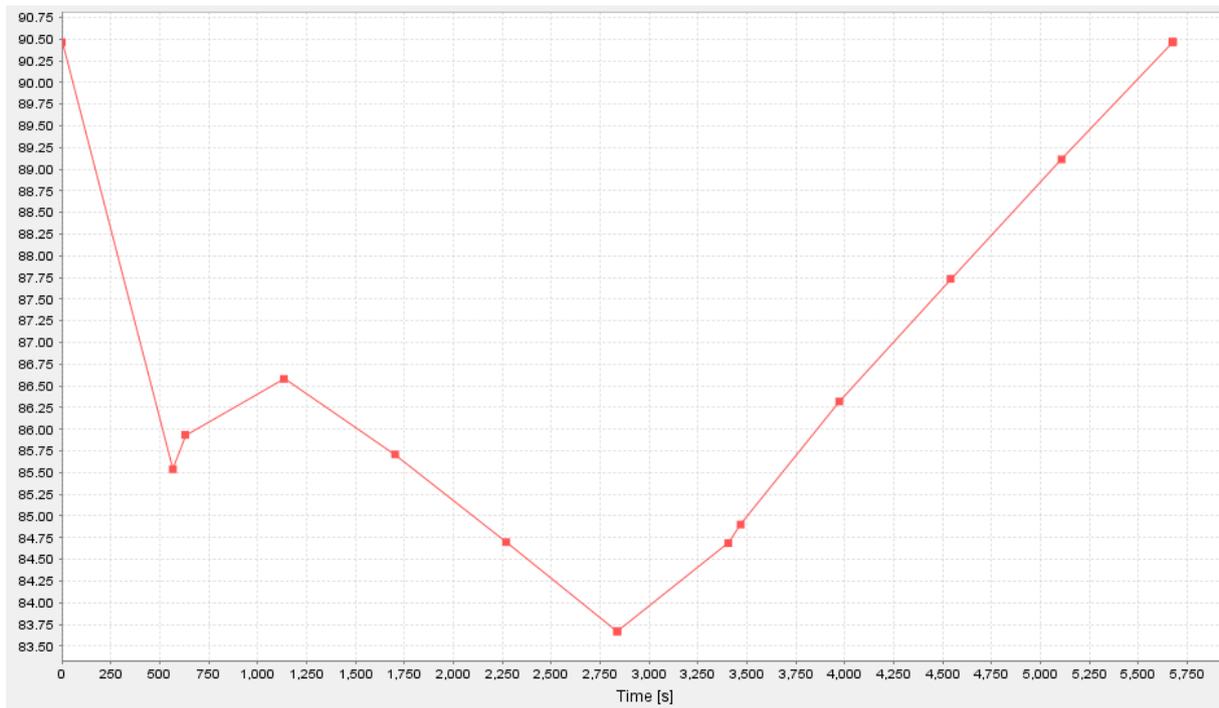


Figure 5-1 Nominal Sunpointing temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

Table 5-1 Nominal Sunpointing temperature limit

| ID | LoLo | Lo | Min uncertainty | Min | Max | Max uncertainty | Hi | HiHi |
|-----------|--------|--------|-----------------|--------|-------|-----------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 17.58 | 22.58 | 25.98 | 30.98 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 19.48 | 24.48 | 28.23 | 33.23 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 18.82 | 23.82 | 26.66 | 31.66 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 16.56 | 21.56 | 24.94 | 29.94 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -11.585 | -6.585 | 12.28 | 17.28 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -10.826 | -5.826 | 6.653 | 11.653 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 15.14 | 20.14 | 23.15 | 28.15 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 25.81 | 30.81 | 34.98 | 39.98 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | 19.97 | 24.97 | 27.86 | 32.86 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 18.10 | 23.10 | 25.99 | 30.99 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | 35.86 | 38.86 | 46.34 | 51.34 | 70.00 | 80.00 |

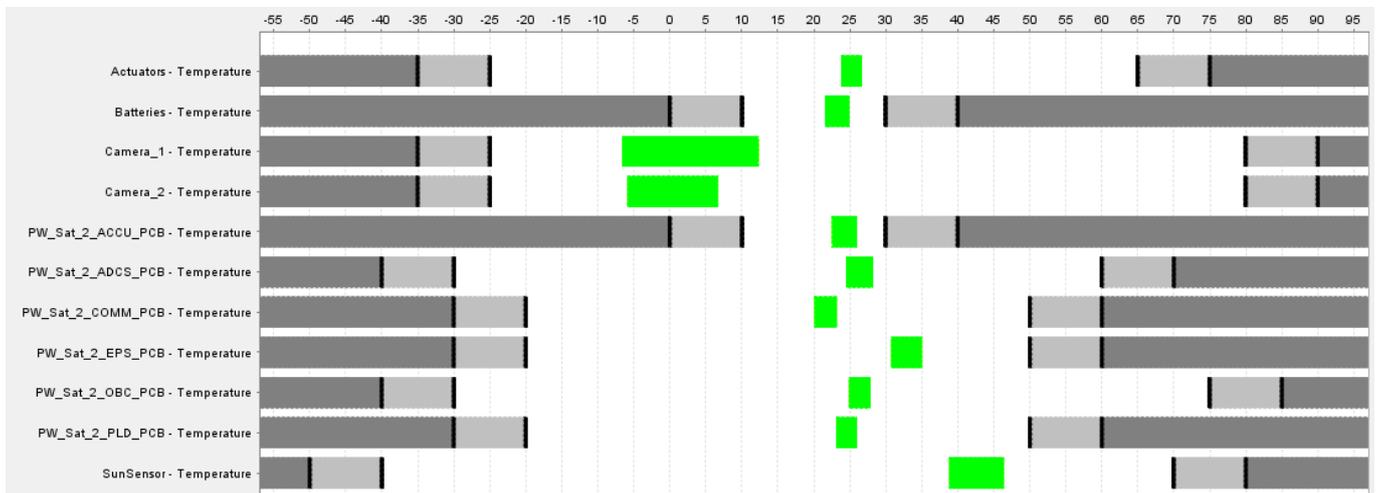


Figure 5-2 Nominal Sunpointing case temperature limit graph

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

5.1.2 ADCS FAILURE RESULTS

This subchapter contains results of the ADCS failure case (see chapter 4.2), which is considered to be one of the coldest case that will result. During this case, failure of ADCS is considered, resulting in a very low heat dissipation and constant, unrestrained rotation of a satellite.

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

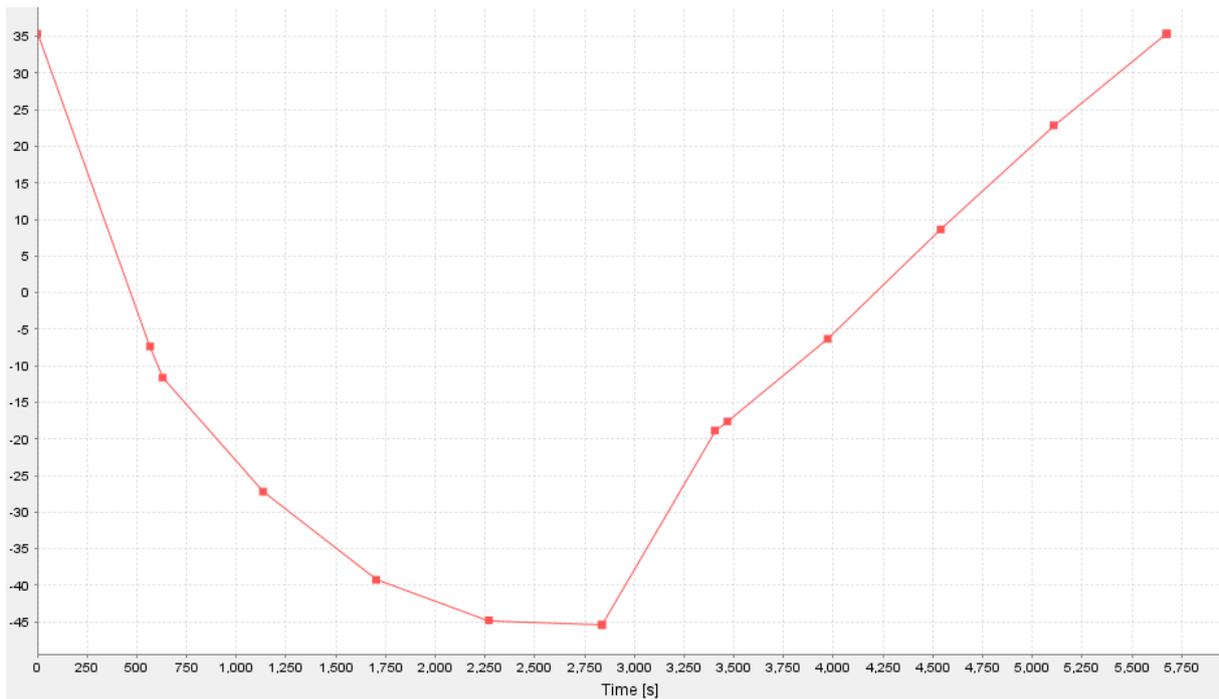


Figure 5-3 ADCS_failure case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

Table 5-2 ADCS failure case temperature limit

| ID | LoLo | Lo | Min - uncertainty | Min | Max | Max + uncertainty | Hi | HiHi |
|-----------|--------|--------|----------------------|--------|-------|----------------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 5.88 | 10.88 | 12.18 | 17.18 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 6.80 | 11.80 | 13.51 | 18.51 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 6.50 | 11.50 | 12.66 | 17.66 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 5.44 | 10.44 | 12.43 | 17.43 | 30.00 | 40.00 |
| Cam_1 | -35.00 | -25.00 | -13.204 | -8.204 | 7.724 | 12.724 | 80.00 | 90.00 |
| Cam_2 | -35.00 | -25.00 | -12.603 | -7.603 | 16.97 | 21.97 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 4.544 | 9.544 | 11.64 | 16.64 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 9.34 | 14.34 | 16.11 | 21.11 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | 8.21 | 13.21 | 15.20 | 20.20 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 4.157 | 9.157 | 10.64 | 15.64 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -5.288 | -0.288 | 0.429 | 5.429 | 70.00 | 80.00 |

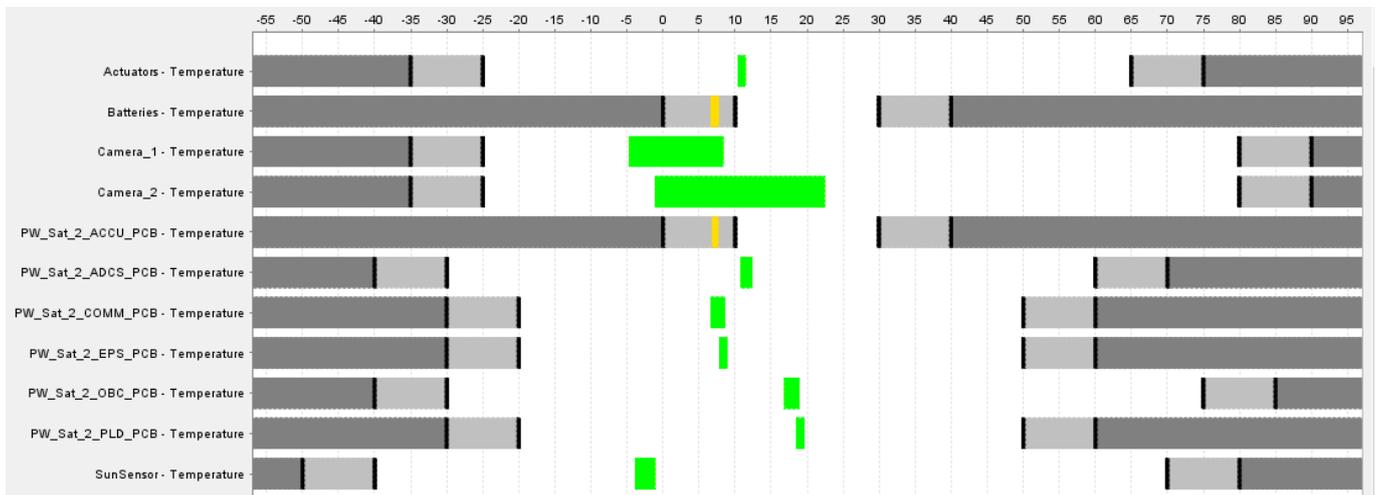


Figure 5-4 ADCS failure case temperature limit graph

5.1.3 DETUMBLING RESULTS

This subchapter contains results of a potential hot or cold case (see chapter 4.3), which may result due to the high heat generation, and rapid rotation of the satellite.

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

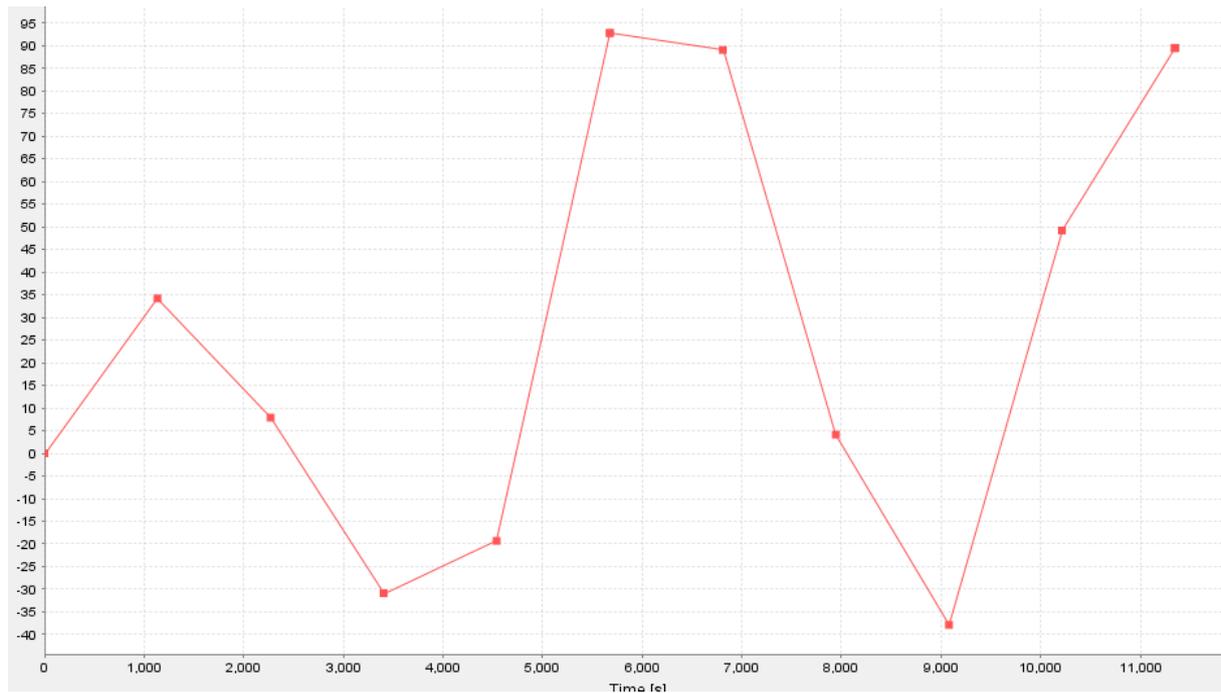


Figure 5-5 Detumbling case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

Table 5-3 Detumbling case temperature limit

| ID | LoLo | Lo | Min uncertainty | Min | Max | Max uncertainty | Hi | HiHi |
|-----------|--------|--------|-----------------|--------|-------|-----------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | -5.000 | 0.000 | 8.309 | 13.309 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | -5.000 | 0.000 | 18.55 | 23.55 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | -5.000 | 0.000 | 20.89 | 25.89 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | -5.000 | 0.000 | 7.748 | 12.748 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -16.28 | -11.28 | 34.41 | 39.41 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -11.903 | -6.903 | 43.70 | 48.70 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 7.734 | 12.734 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 15.10 | 20.10 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | -5.000 | 0.000 | 13.02 | 18.02 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 8.158 | 13.158 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -5.000 | 0.000 | 4.810 | 9.810 | 70.00 | 80.00 |

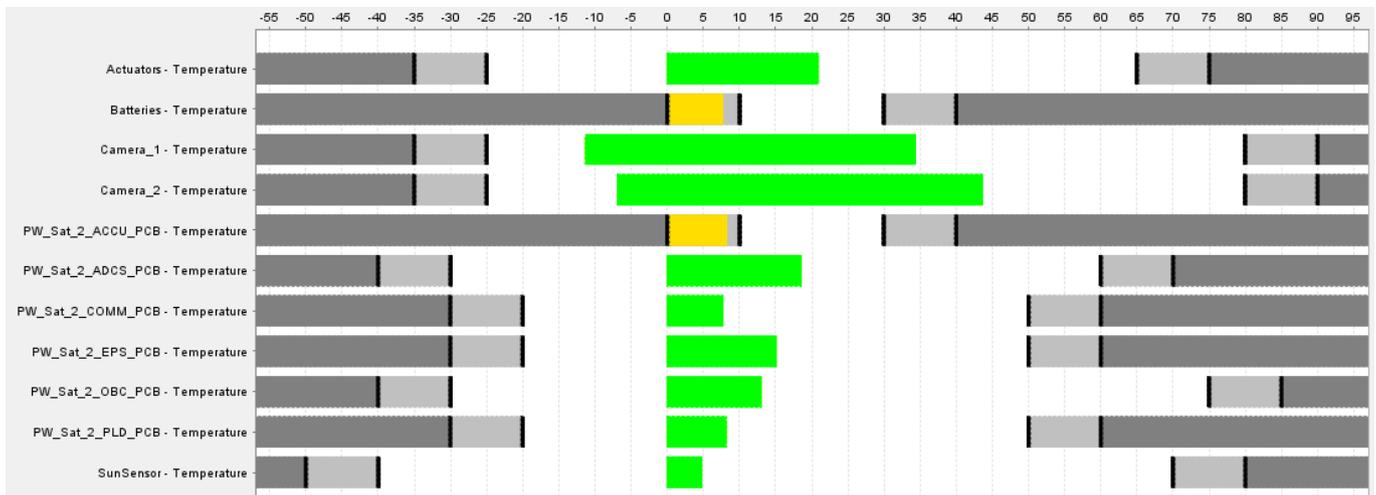


Figure 5-6 Detumbling case temperature limit graph

5.1.4 SUNPOINTING RESULTS

This subchapter contains results of a Sunpointing analysis case. In this case, obtained temperatures should not exceed results from neither Detumbling nor Nominal Sunpointing, as this case is a transition between aforementioned two cases.

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

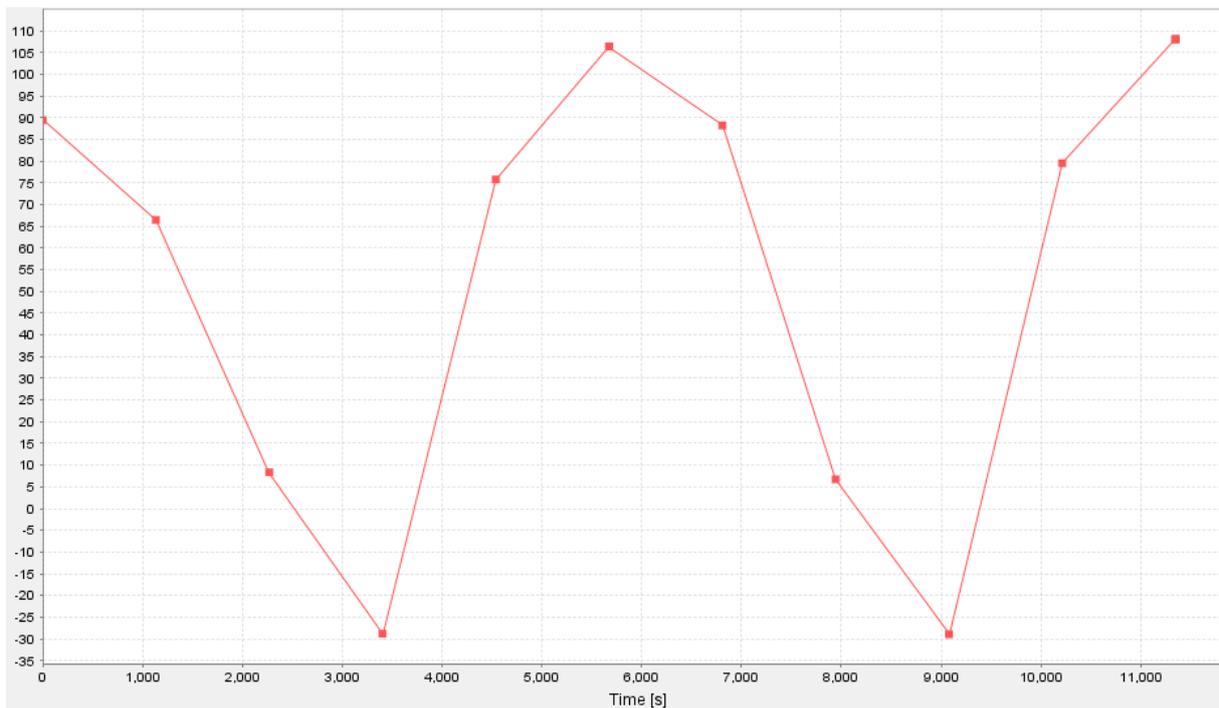


Figure 5-7 Sunpointing case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

Table 5-4 Sunpointing case temperature limit

| ID | LoLo | Lo | Min - uncertainty | Min | Max | Max + uncertainty | Hi | HiHi |
|-----------|--------|--------|-------------------|-------|-------|-------------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 2.019 | 7.019 | 16.00 | 21.00 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 11.08 | 16.08 | 27.77 | 32.77 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 15.20 | 20.20 | 30.66 | 35.66 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 1.862 | 6.862 | 15.36 | 20.36 | 30.00 | 40.00 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

| | | | | | | | | |
|-----------|--------|--------|---------|--------|-------|-------|-------|-------|
| Camera_1 | -35.00 | -25.00 | -14.836 | -9.836 | 33.26 | 38.26 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -15.18 | -10.18 | 40.03 | 45.03 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 1.895 | 6.895 | 13.42 | 18.42 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 9.28 | 14.28 | 24.06 | 29.06 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | 7.53 | 12.53 | 21.05 | 26.05 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 1.962 | 6.962 | 14.37 | 19.37 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -3.945 | 2.945 | 15.30 | 20.30 | 70.00 | 80.00 |

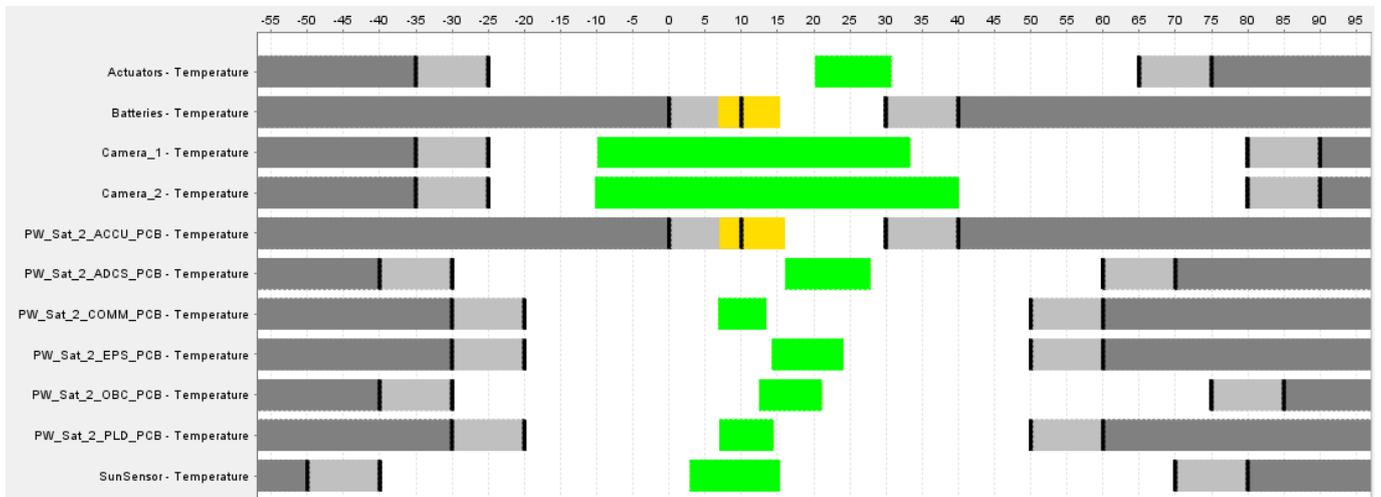


Figure 5-8 Sunpointing case temperature limit graph

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

5.2 CLOSED SOLAR PANELS

Thermal analyses of a satellite with closed solar panels were performed for a geometric model shown on a Figure 6-9.

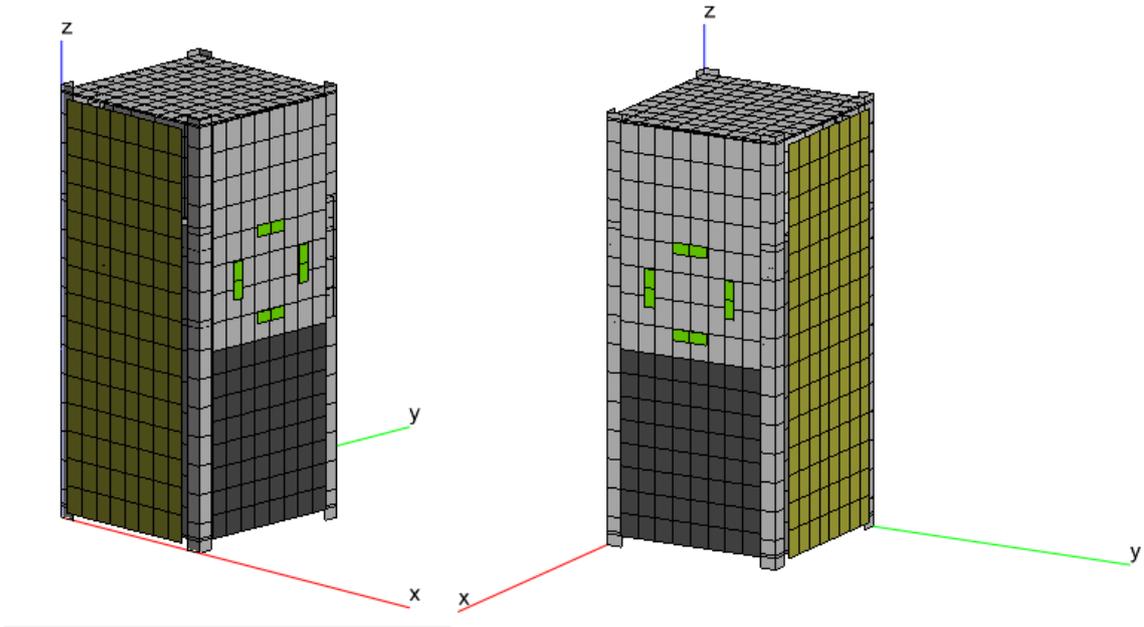


Figure 5-9 Geometry with closed solar panels

5.2.1 NOMINAL SUNPOINTING RESULTS

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

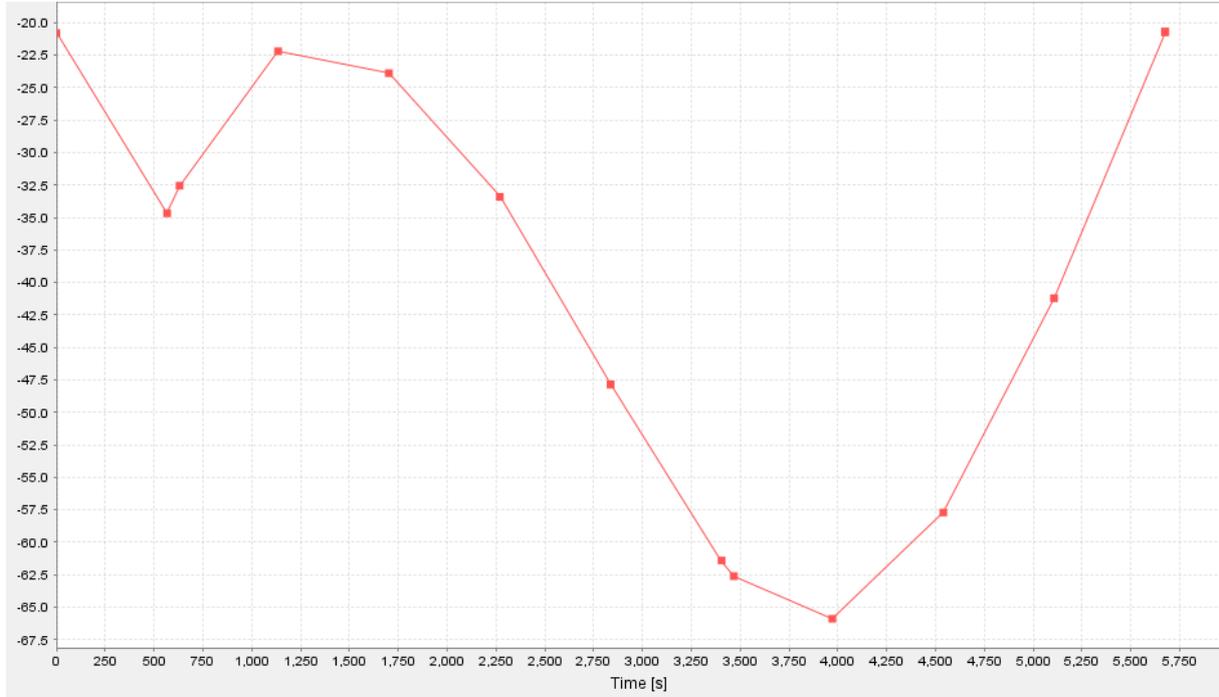


Figure 5-10 Nominal Sunpointing temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

Table 5-5 Nominal Sunpointing temperature limit

| ID | LoLo | Lo | Min - uncertainty | Min | Max | Max + uncertainty | Hi | HiHi |
|-----------|--------|--------|----------------------|--------|-------|----------------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 20.02 | 25.02 | 28.31 | 33.31 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 22.91 | 27.91 | 31.29 | 36.29 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 22.27 | 27.27 | 30.25 | 35.25 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 18.59 | 23.59 | 27.33 | 32.33 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -13.074 | -8.074 | 8.157 | 13.157 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -8.385 | -3.385 | 4.369 | 9.369 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 15.97 | 20.97 | 24.19 | 29.19 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 29.06 | 34.06 | 38.35 | 43.35 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | 22.15 | 27.15 | 29.90 | 34.90 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 18.63 | 23.63 | 26.29 | 31.29 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | 15.53 | 20.53 | 31.86 | 36.86 | 70.00 | 80.00 |

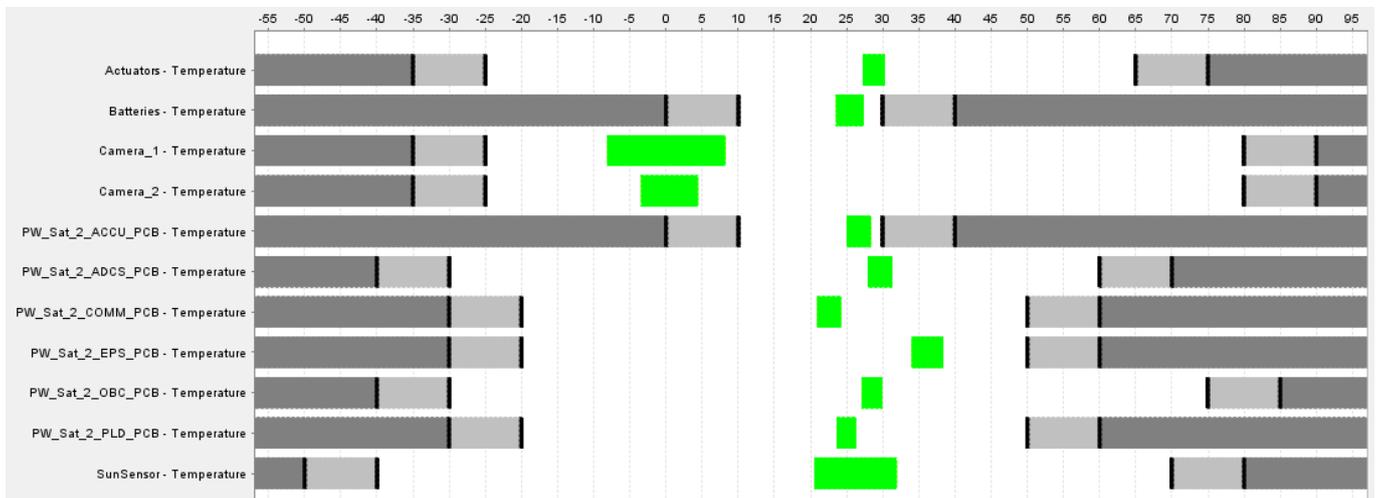


Figure 5-11 Nominal Sunpointing case temperature limit graph

5.2.2 ADCS FAILURE RESULTS

Temperatures distribution in time over the orbit at solar panels are presented below.

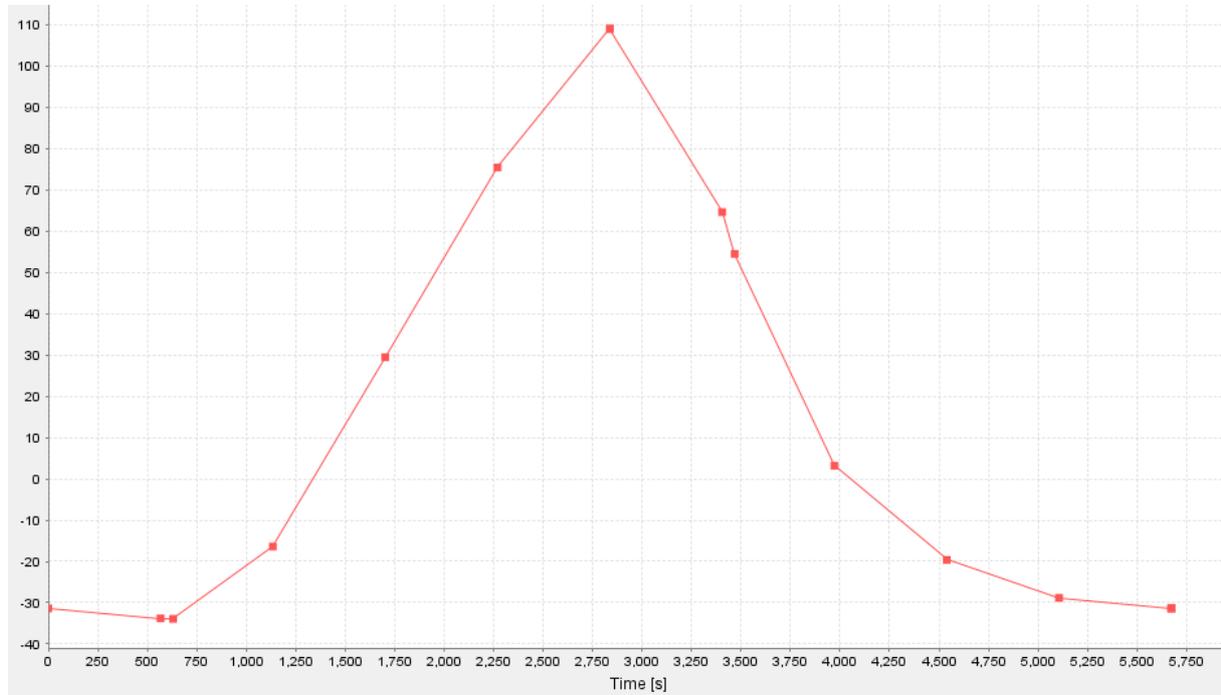


Figure 5-12 ADCS_failure case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

Table 5-6 ADCS failure case temperature limit

| ID | LoLo | Lo | Min - uncertainty | Min | Max | Max + uncertainty | Hi | HiHi |
|-----------|--------|--------|----------------------|--------|-------|----------------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 1.805 | 6.805 | 7.662 | 12.662 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 5.83 | 10.83 | 12.36 | 17.36 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 5.38 | 10.38 | 11.41 | 16.41 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 1.620 | 6.620 | 7.785 | 12.785 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -9.642 | -4.642 | 8.322 | 13.322 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -6.045 | -1.045 | 22.41 | 27.41 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 1.644 | 6.644 | 8.571 | 13.571 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 2.813 | 7.813 | 8.915 | 13.915 | 50.00 | 60.00 |

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

| | | | | | | | | |
|-----------|--------|--------|--------|--------|--------|-------|-------|-------|
| OBC_PCB | -40.00 | -30.00 | 11.87 | 16.87 | 18.88 | 23.88 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 13.50 | 18.50 | 19.62 | 24.62 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -8.862 | -3.862 | -1.133 | 4.133 | 70.00 | 80.00 |

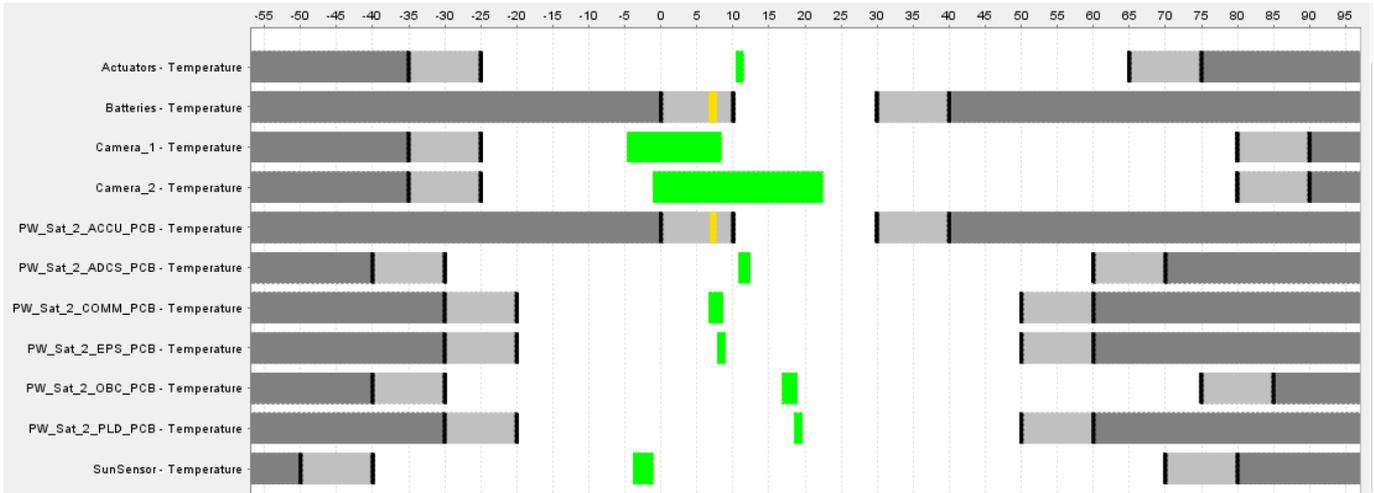


Figure 5-13 ADCS failure case temperature limit graph

5.2.3 DETUMBLING RESULTS

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

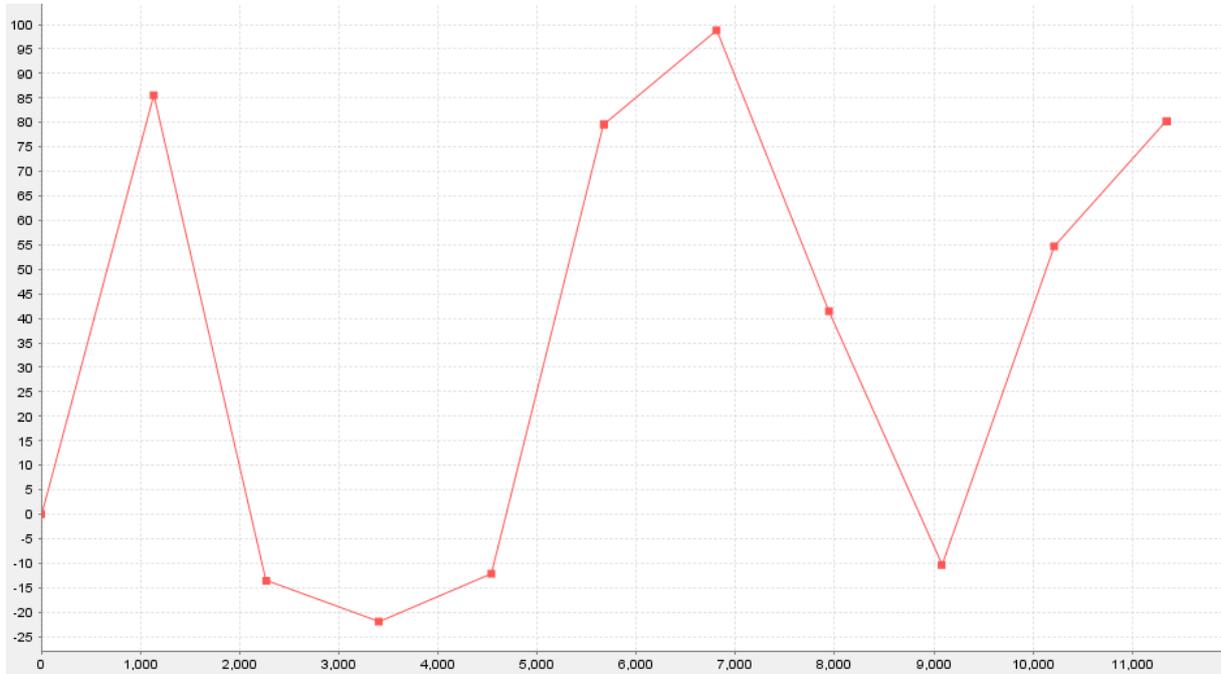


Figure 5-14 Detumbling case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

Table 5-7 Detumbling case temperature limit

| ID | LoLo | Lo | Min uncertainty | Min | Max | Max uncertainty | Hi | HiHi |
|-----------|--------|--------|-----------------|--------|-------|-----------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | -5.000 | 0.000 | 7.247 | 12.247 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | -5.000 | 0.000 | 17.07 | 22.07 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | -5.000 | 0.000 | 19.37 | 24.37 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | -5.000 | 0.000 | 6.745 | 11.745 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -17.28 | -12.28 | 34.45 | 39.45 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -7.630 | -2.630 | 21.89 | 26.89 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 6.839 | 11.839 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 13.76 | 18.76 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | -5.000 | 0.000 | 11.69 | 16.69 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | -5.000 | 0.000 | 6.986 | 11.986 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -5.000 | 0.000 | 2.065 | 7.065 | 70.00 | 80.00 |

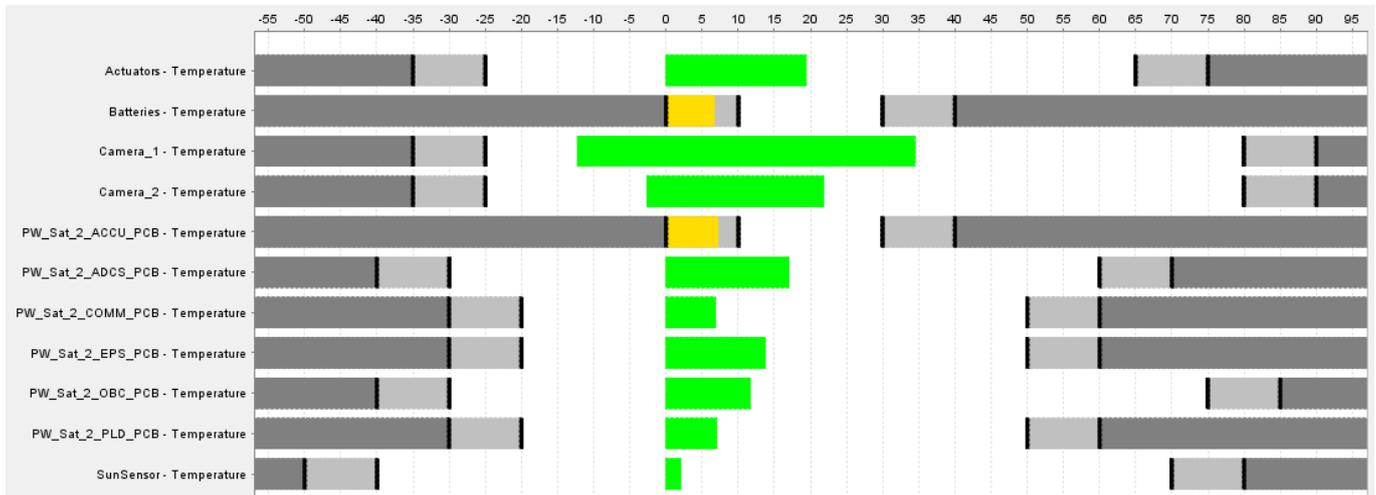


Figure 5-15 Detumbling case temperature limit graph

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

5.2.4 SUNPOINTING RESULTS

Temperatures distribution in time over the orbit at solar panels are presented below to show the time of eclipse phase.

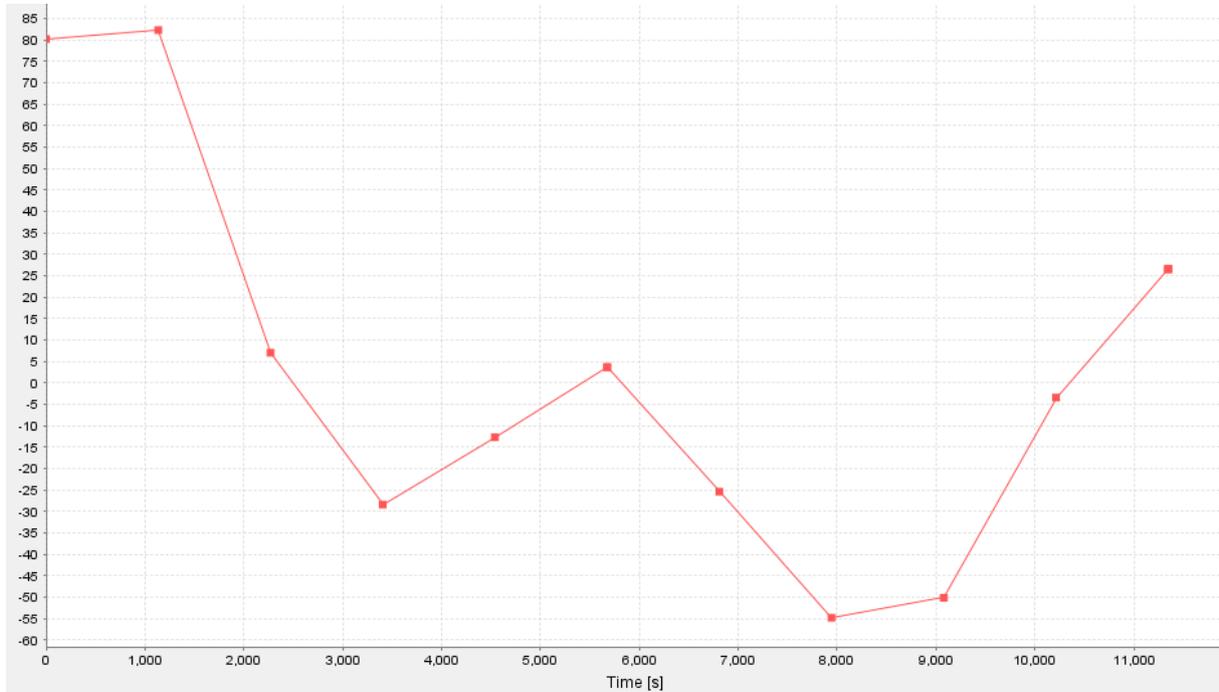


Figure 5-16 Sunpointing case temperature distribution in time (solar panel)

Maximal and minimal temperature results and their limits at the most crucial components were presented in the table below.

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

Table 5-8 Sunpointing case temperature limit

| ID | LoLo | Lo | Min - uncertainty | Min | Max | Max + uncertainty | Hi | HiHi |
|-----------|--------|--------|----------------------|--------|-------|----------------------|-------|-------|
| ACCU_PCB | 0.000 | 10.000 | 0.992 | 5.992 | 14.10 | 19.10 | 30.00 | 40.00 |
| ADCS_PCB | -40.00 | -30.00 | 9.66 | 14.66 | 25.70 | 30.70 | 60.00 | 70.00 |
| Actuators | -35.00 | -25.00 | 13.70 | 18.70 | 28.52 | 33.52 | 65.00 | 75.00 |
| Batteries | 0.000 | 10.000 | 0.861 | 5.861 | 13.52 | 18.52 | 30.00 | 40.00 |
| Camera_1 | -35.00 | -25.00 | -15.53 | -10.53 | 33.63 | 38.63 | 80.00 | 90.00 |
| Camera_2 | -35.00 | -25.00 | -9.796 | -4.796 | 19.91 | 24.91 | 80.00 | 90.00 |
| COMM_PCB | -30.00 | -20.00 | 0.938 | 5.938 | 11.60 | 16.60 | 50.00 | 60.00 |
| EPS_PCB | -30.00 | -20.00 | 7.97 | 12.97 | 22.01 | 27.01 | 50.00 | 60.00 |
| OBC_PCB | -40.00 | -30.00 | 6.19 | 11.19 | 19.07 | 24.07 | 75.00 | 85.00 |
| PLD_PCB | -30.00 | -20.00 | 0.736 | 5.736 | 12.44 | 17.44 | 50.00 | 60.00 |
| SunSensor | -50.00 | -40.00 | -5.904 | 0.904 | 7.104 | 12.104 | 70.00 | 80.00 |

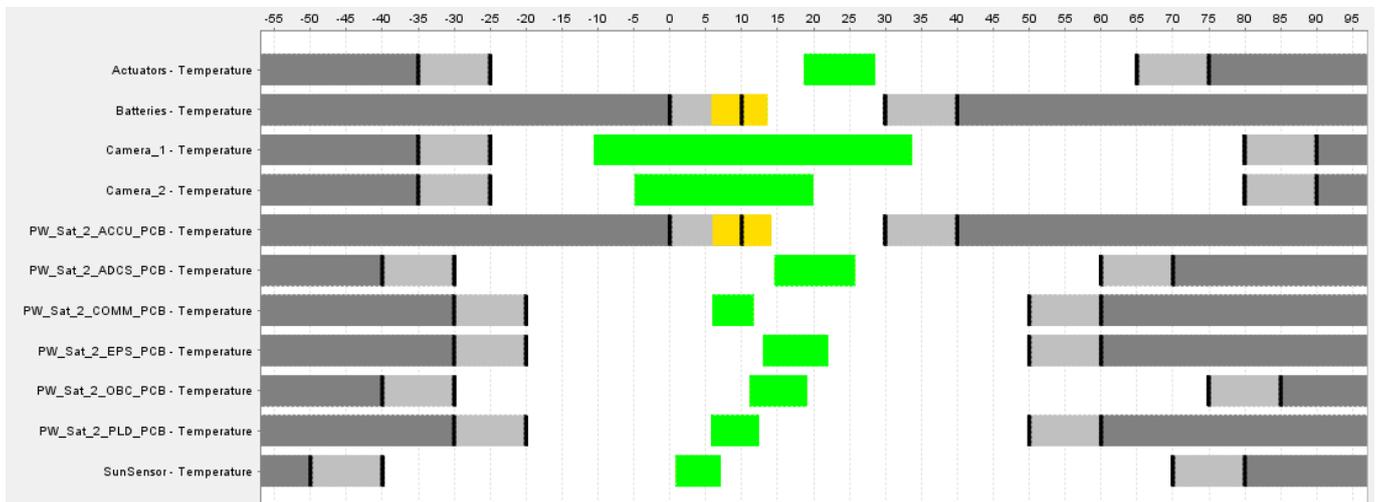


Figure 5-17 Sunpointing case temperature limit graph

| | | | |
|---|------------|------------------------|---|
|  | PW-Sat2 | Critical Design Review |  |
| | 2016-11-30 | Thermal Control System | |
| | Phase C | | |

6 CONCLUSIONS

Based on the results presented in chapter 5, no extreme temperatures were found for the most probable cases to occur, during PW-Sat2 mission.

For the most basic case – Nominal Sunpointing – all temperatures are within their limits, with no threat to qualification limits. For a case, where solar panels fails to open, a small problem with batteries temperatures may occur. From the possible cases, this one is considered to be the hot case.

For detumbling, the lowest resulting temperatures are at 0°C due to the initial temperatures set at those value. Because of the detumbling nature, no cyclic solution was initialized. Those temperatures, should be considered to be 1~2 degrees higher.

For most non-nominal cases, the temperatures on batteries are close to their lower limit, but it is important to note, that the batteries have built-in heaters, that were not considered in the analyses. Their need to use must be taken into consideration during mission planning and energy budgeted estimation to prevent batteries from overcooling in certain situations, especially during eclipse.