GALILEO GALILEI (GG)

THERMAL DESIGN AND ANALYSIS REPORT

DRL/DRD: DEL-23/24/33/35

Written by	***Responsibility***
M. Compassi	Author
Verified by	
n.a.	Checker
Approved by	
	Product Assurance
	Configuration Control
	Design Engineer
	System Engineering Manager
A. Anselmi	Study Manager
Documentation Manager	
R. Cavaglià	

The validations evidence are kept through the documentation management system.

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
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1. SCOPE AND PURPOSE

This document is submitted in partial fulfilment of Work Package 1A-ADA of the GG Phase A2 Study (DRL item DEL-23/24/33/35).

The purpose of the document is to provide the description of the geometrical and thermal mathematical models built for GG as well as the presentation of the temperature results obtained from Flight thermal analysis performed.

Scope of the thermal control is to maintain all the equipment items within their temperature ranges according to the item's status (operative/not operative) for all mission phase duration.

In addition a suitable thermal conditioning of PGB environment shall be provided in order to guarantee temperature stability during time as well as axial temperature gradient requirement and temperature fluctuations on test masses.

2. REFERENCES

2.1 Applicable Documents

[AD 1] ASI, "Progetto Galileo Galilei-GG Fase A-2, Capitolato Tecnico", DC-IPC-2007-082, Rev. B, 10-10-2007 and applicable documents defined therein

2.2 ASI Reference Documents

[RD 1] GG Phase A Study Report, Nov. 1998, revised Jan. 2000, available at: http://eotvos.dm.unipi.it/nobili/ggweb/phaseA/index.html

[RD 2] Supplement to GG Phase A Study (GG in sun-synchronous Orbit) "Galileo Galilei-GG": design, requirements, error budget and significance of the ground prototype", A.M. Nobili et al., Physics Letters A 318 (2003) 172–183, available at: http://eotvos.dm.unipi.it/nobili/documents/generalpapers/GG_PLA2003.pdf

[RD 3] A. Nobili, DEL001: GG Science Requirements, Pisa, September 2008

2.3 GG Phase A2 Study Notes

[RD 4] SD-RP-AI-0625, GG Final Report / Satellite Detailed Architecture Report, Issue 1

[RD 5] SD-RP-AI-0626, GG Phase A2 Study Executive Summary, Issue 1

[RD 6] SD-TN-AI-1163, GG Experiment Concept and Requirements Document, Issue 3

[RD 7] SD-RP-AI-0620, GG System Performance Report, Issue 2

[RD 8] SD-TN-AI-1167, GG Mission Requirements Document, Issue 2

[RD 9] SD-RP-AI-0590, GG System Concept Report (Mission Description Document), Issue 3

[RD 10] SD-SY-AI-0014, GG System Functional Specification and Preliminary System Technical Specification, Issue 1

[RD 11] SD-RP-AI-0631, GG Consolidated Mission Description Document, Issue 1

[RD 12] SD-TN-AI-1168, GG Mission Analysis Report, Issue 2

[RD 13] DTM, GG Structure Design and Analysis Report, Issue 1

[RD 14] SD-RP-AI-0627, GG Thermal Design and Analysis Report, Issue 1

[RD 15] SD-RP-AI-0268, GG System Budgets Report, Issue 1

[RD 16] SD-RP-AI-0621, Technical Report on Drag and Attitude Control, Issue 2

[RD 17] TL25033, Payload Architectures and Trade-Off Report, Issue 3

[RD 18] SD-RP-AI-0629, Technical Report on Simulators, Issue 1

[RD 19] ALTA, FEEP Thruster Design and Accommodation Report, Issue 1

[RD 20] TAS-I, Cold-Gas Thruster Design and Accommodation Report, Issue 1

[RD 21] SD-RP-AI-0630, Spin Sensor Design, Development and Test Report, Issue 1

[RD 22] SD-TN-AI-1169, GG Launcher Identification and Compatibility Analysis Report, Issue 1

[RD 23] ALTEC-AD-001, GG Ground Segment Architecture and Design Report, Issue 1

[RD 24] SD-TN-AI-1218, GG Preliminary Product Tree, Issue 1

[RD 25] SD-PL-AI-0227, GG System Engineering Plan (SEP), Issue 2

[RD 26] TAS-I, Payload Development and Verification Plan, Issue 1

[RD 27] SD-PL-AI-0228, GG System Verification and Validation Plan, Issue 1

[RD 28] SD-TN-AI-1219, Report on Frequency Management Issues, Issue 1

[RD 29] SD-RP-AI-0632, GG Mission Risk Assessment And Mitigation Strategies Report, Issue 1

[RD 30] SD-RP-AI-0633, Report on Mission Costs Estimates, Issue 1

2.4 List of acronyms

BOL	Beginning Of Life
EOL	End Of Life
GMM	Geometrical Mathematical Model
TMM	Thermal Mathematical Model
MLI	Multi Layer Insulation
PGB	Pico Gravity Box

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3. GALILEO GALILEI (GG) MODEL DESCRIPTION

The primary TCS target for the GG mission is to guarantee the proper thermal environment for all the equipment items and to maintain the temperature stability/gradient requirement on test masses inside the PGB.

A classical passive approach plus heaters has been selected:

- The external side of the S/C will be covered by MLI blankets to counter the environment loads; painted radiators areas are distributed on the cylindrical structure following the footprint of the electronic boxes mounted inside the structural cylinder; solar arrays cells are placed on two dedicated cylindrical sections.
- The internal side of the S/C will be black-painted as much as possible where power is generated (internal cylindrical section and electronic boxes) in order to minimize temperature gradients, while a low emissivity surface finish has been selected for both the external and the internal side of the PGB in order to radiatively decouple the payload from the remaining parts of the S/C.
- Electronics are mounted on the internal cylindrical structure via thermal doublers/fillers to increase the baseplate contact conductance; the PGB is conductively decoupled as much as possible from the remaining parts of the S/C, and the core of the payload is connected to the support structures via Copper-Beryllium springs.
- The use of standard electrical heaters to trim or maintain the necessary temperature levels; this solution will be limited to the electronic boxes area since no heaters are envisaged inside the PGB enclosure in order to limit oscillation and temperature disturbances to the test masses.

The following thermal hardware is foreseen at this level of analysis:

<u>MLI Blankets</u>
Multi Layer Insulation blankets will be 20-layers ITO Kapton with Dacron net spacers; the MLI will cover all the external surfaces except the radiators, solar cells and mechanical I/F with launch adapters. The MLI composition is defined as follows:

- 1 outer layer of ITO Kapton 1 mil
- 1 layer Dacron net
- 18 x (1 layer of Double Aluminized Mylar (0.25 mil) perforated; 1 layer Dacron net)
- 1 bottom layer of Double Aluminized Kapton

On internal environment a low emissivity MLI blankets 20-layers Double Aluminized Kapton will also be used on the PGB cylinder; the MLI composition is defined as follows

- 1 outer layer of Double Aluminized 1 mil
- 1 layer Dacron net

- 18 x (1 layer of Double Aluminized Mylar (0.25 mil) perforated; 1 layer Dacron net)
- 1 bottom layer of Double Aluminized Kapton

Surface Finishes

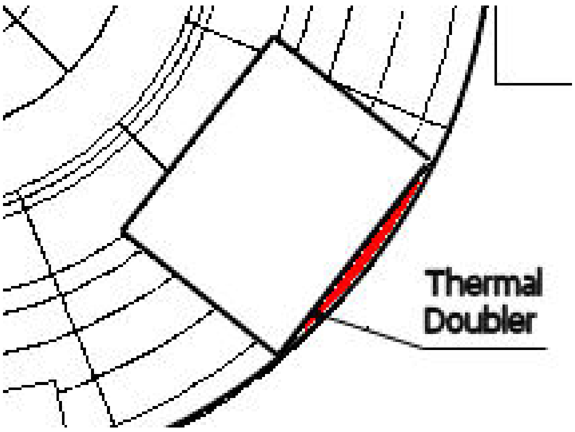
Black paint Aeroglaze Z306 will be used for the internal side of the structural cylinder as finish of the electronic boxes.
Test masses and Capacitive Plates are foreseen with a Gold finish (low emissivity values).
All the remaining parts of the internal environments will have a low-emissivity finish, not exceeding 0.05.
The external radiator areas will be covered with silvered Teflon tape.

Thermal fillers

Sigraflex-F will be used to increase thermal coupling between equipments and the mounting surfaces (brackets or structural panels)

Thermal doublers

In order to mount the internal units on the cylindrical structure panel an aluminium thermal doubler has been considered under each unit between unit and external radiator. The purpose of this doubler is to fill the gap between unit and the structure panel and optimize the contact conductance to the external radiator.



3.1 GMM Model description

The Geometrical Mathematical Model (GMM) has been build using ESARAD software (version 6.2) in order to compute the internal and external radiative exchange factors between surfaces and the external fluxes (Solar, Albedo and Infrared) computation.
The GMM includes all the main structural elements, the payload components, and the equipments both inside and outside the S/C:

- Structural main cylinder, cones, flanges and payload support structures
- Internal electronic boxes
- PGB protective cylinder, I/F flanges and springs
- Payload internals: Mass 1, Mass2, Capacitive Plates, and support cylinders brackets and flanges
- External MLI blankets, sensors, antennas and Solar Arrays

The following figures depict the modeled elements from the internal to external surfaces:

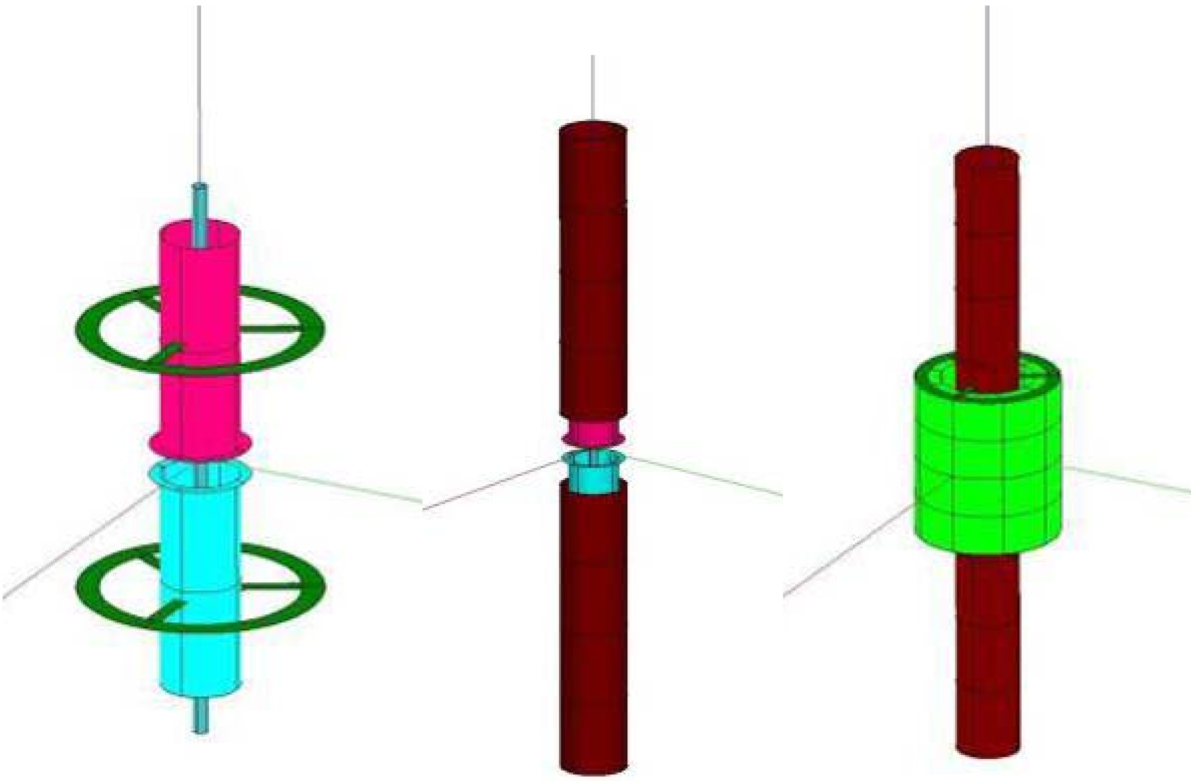


Figure 3.1-1 GG - Payload internal cylinders, Support flanges, Upper & Lower Shaft, Test Mass M1

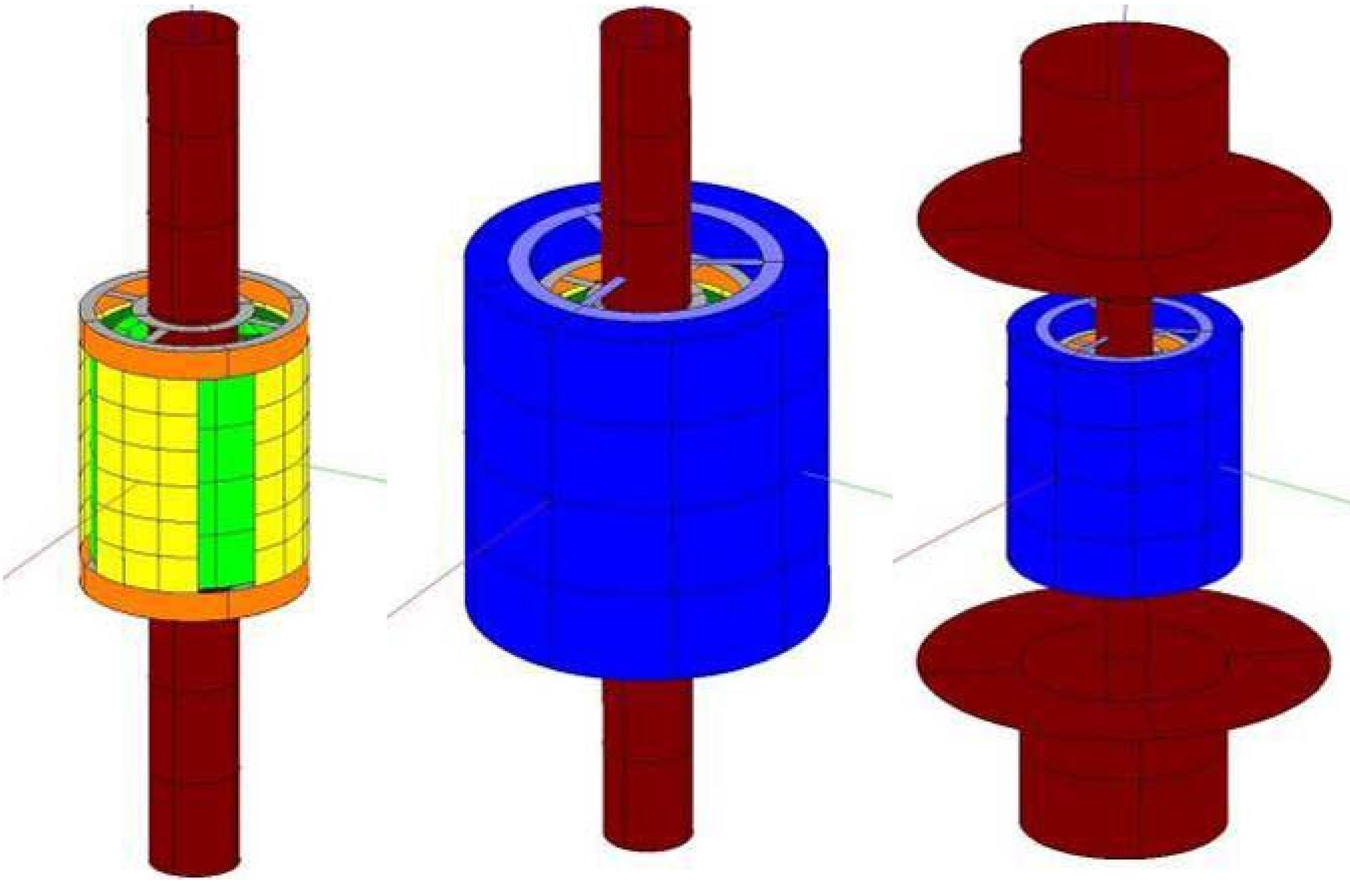


Figure 3.1-2 GG - Payload Capacitive Plates, Test Mass 2, PGB I/F structure

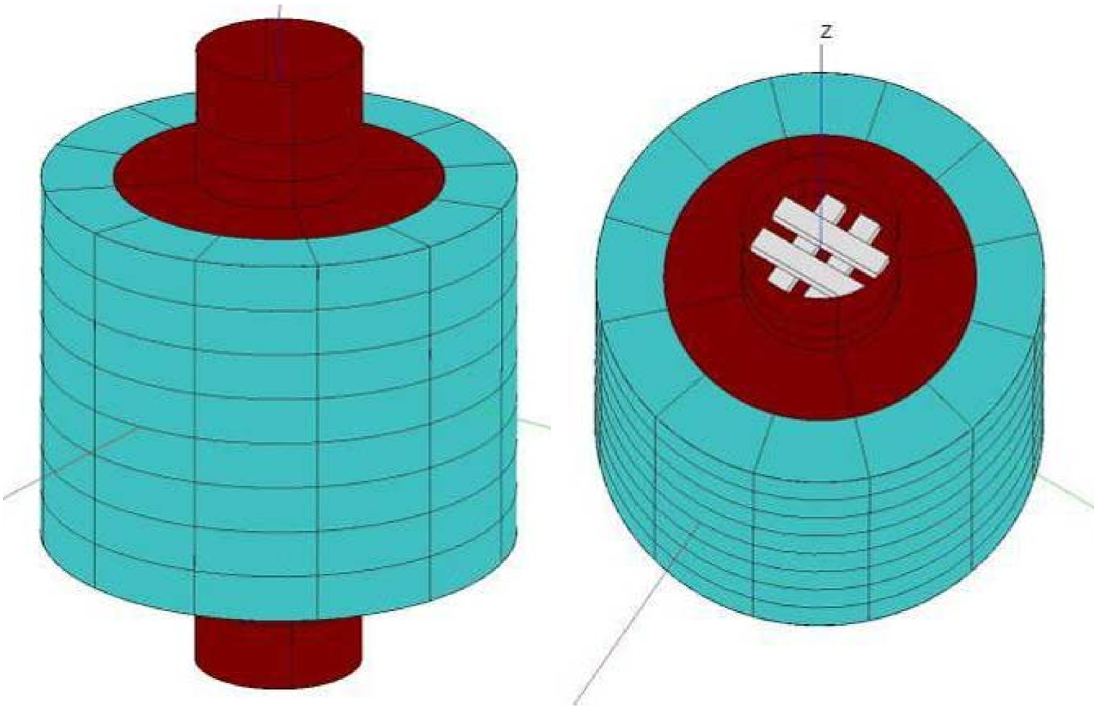


Figure 3.1-3 GG - PGB, PGB I/F structure, Cu-Be Springs

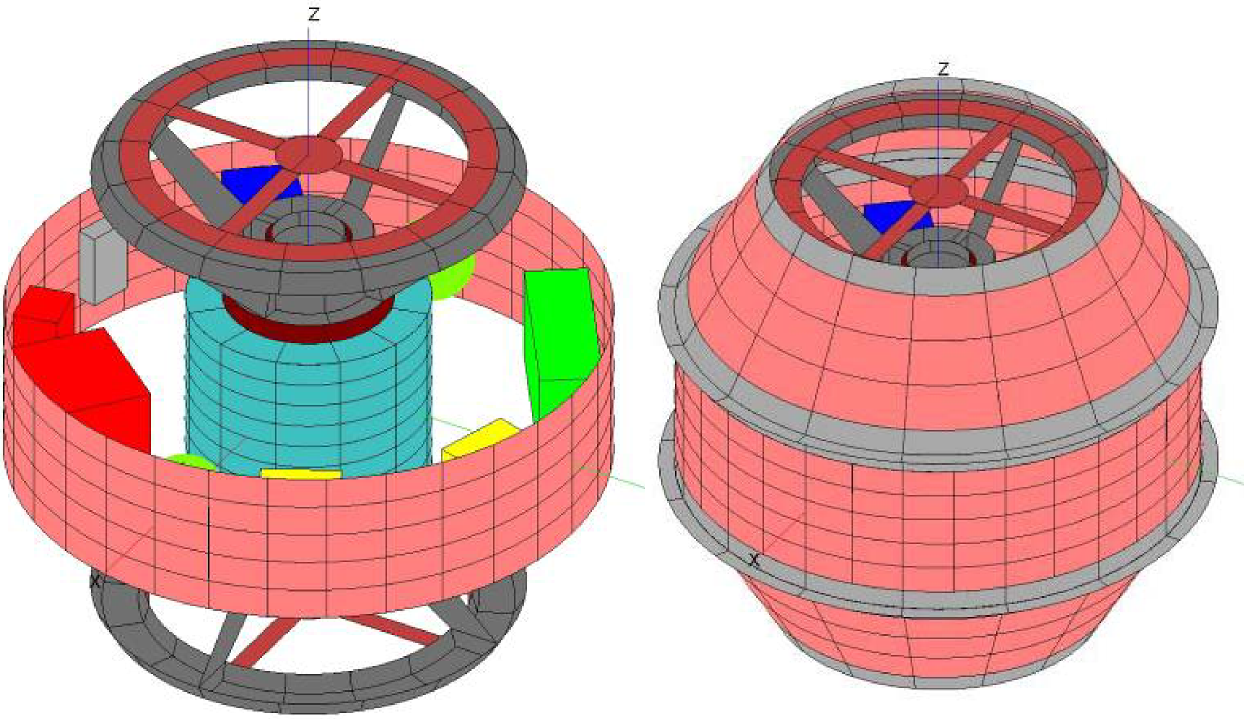


Figure 3.1-4 GG – S/C support cone and internal units, external panels (cone, cylinder I/F rings)

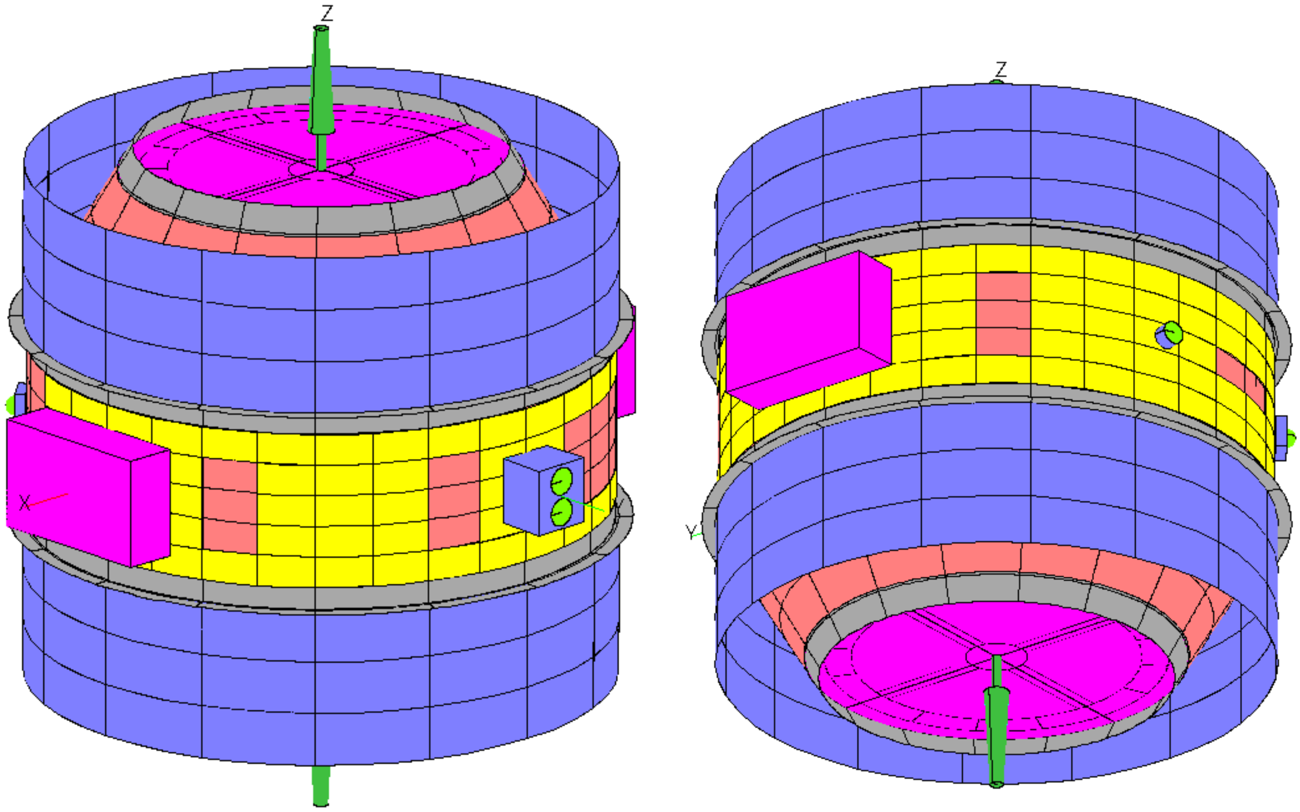


Figure 3.1-5 GG – Overall external view

The nodal breakdown of all thermal nodes is reported in Annex 1

3.1.1 GG - Surface finishes and thermo-optical properties

A summary of the thermo-optical properties related to the surface finishes used in the Geometrical model is presented in the following table; solar absorptivity degradation due to cumulative exposition to external orbit environment has been taken into account

Thermo-Optical properties

Surface finish	Solar Absorptivity Beginning of Life α BOL	Solar Absorptivity End of life α EOL	Emissivity ε	Note
MLI ITO Kapton	0.30	0.43	0.77	External Structure (Cylinder panel)
MLI Aluminised Kapton	0.14	0.14	0.05	External Structure (Cone panels)
Black paint Z306	0.96	0.96	0.88	Internal structure (panels), Units, Solar Array back side
Silvered Teflon tape	0.14	0.30	0.75	External Radiator
Bare aluminium	0.21	0.21	0.05	Internal Structure support
Solar Array Cell Side	0.75	0.75	0.82	Solar Array Cell
White Paint	0.23	0.65	0.88	Antenna
Gold finish	0.04	-	-	Test Masses 1 & 2 Capacitive Plates

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3.1.2 GG – Radiator and MLI area

The external radiative areas have been covered with a Silver Teflon tape and positioned only on the outer cylindrical structure panel in correspondence of the internal boxes arrangement.
The current radiative areas implemented in the geometrical model for each unit are reported in the following table.

Unit	Radiator area [m^2]
Battery	0.0222
PCE	0.0334
CDMU	0.1001
TRANSP 1	0.0334
TRANSP 2	0.0334
PCU	0.1557
Tot Radiative area [m^2]	**0.378**

External surfaces not used as radiator are covered by MLI (20 layers) and their current distribution is here reported (internal MLI also included):

Location	MLI area [m^2]
Closure Disc upper	0.769
Closure Disc lower	0.769
Structure Cone upper	1.888
Structure Cone lower	1.888
Structure Cylinder	1.915
FEEP + Ext. items	1.024
Tot Ext MLI area [m^2]	**8.253**
Internal MLI on PGB	1.315
Tot Int MLI area [m^2]	**1.315**

3.2 TMM Model description

The GG's Thermal Mathematical Model (TMM) has been built with Esatan (version 10.2) software and contains all the thermal node definition, the thermal conductivity network and the internal dissipations and thermal loads (unit power and heater dissipation) applied to the relevant thermal nodes.

A list of the material considered in the TMM is presented in the following table:

Ref.	Element	Material	Thermal conductivity	Heat capacity	Density	Comments
 1 2 3	Structural panels: ○ cylinder ○ cones ○ solar arrays	Honeycomb	K_{XY}=7.06 W/m/K K_Z=1.34 W/m/K	900 J/kg/K	2.5 Kg/m^2	Al skin 2*0.4 mm Al core 15 mm
 4 5 6 7 8 9	Structure: ○ rings ○ flanges ○ PGB I/F ○ Payload support structures ○ S/C launcher I/F Payload: ○ brackets, flanges, support cylinders (M1, M2, Capacitive Plates)	Al 7075	150 W/K	900 J/kg/K	2700 Kg/m^3	
10	Mass 1	Tungsten	167 W/m/K	142 J/kg/K	19653 Kg/m^3	
11	Mass 2	Polyethylene	0.33 W/m/K	2301 J/kg/K	941 Kg/m^3	
12	Capacitive Plates	Cu	390 W/K	380 J/kg/K	8920 Kg/m^3	
13	Propellant tanks	Ti	10 W/K	520 J/kg/K	4500 Kg/m^3	
	MLI blankets	20-layer	temperature dependent	0	0	

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3.2.1 GG – conductive couplings

3.2.1.1 MLI conductivity

MLI blankets on external surfaces (FEEP, External items, Cylindrical structure panel) is a 20 layer ITO Kapton 1 mil, with Dacron net spacers; on the external Cone structure panels and on the the internal MLI covering the PGB the MLI considered is a 20 layer with aluminized Kapton. A temperature variable conductive coupling array simulates the MLI conductance behaviour and the array used is reported in the following table:

Temperature [°C]	MLI CONDUCTIVITY [W/m^2/°C]
	20 Layers
-100	0.0175
-90	0.0212
-80	0.0251
-70	0.0292
-60	0.0334
-50	0.0378
-40	0.0424
-30	0.0473
-20	0.0523
-10	0.0577
0	0.0633
10	0.0692
25	0.0786
30	0.0819
40	0.0888
50	0.0960
60	0.1036
70	0.1116
80	0.1200
90	0.1288
100	0.1381

3.2.1.2 Honeycomb Panel conductivity

- Conductive couplings across honeycomb panel (identified as “Z” direction) are calculated by multiplying the effective thermal conductivity Kz and the cross section between two thermal nodes (panel internal / external sides):

$$GL(int,ext) = K_Z * A(node) / d$$

  where
  K_Z = thermal conductivity across the honeycomb [W/m°C]
  A(node) = node area [m2]
  d = overall thickness of the honeycomb panel [m]

- Lateral thermal conductance of honeycomb panel (identified as “XY” direction) is calculated by multiplying the effective thermal conductivity Kxy by the cross section and dividing it by the distance between the two thermal nodes.

$$GL(xxx,yyy) = K_{XY} * A(cross\ section) / d$$

  where
  K_{XY} = in plane conductivity of the honeycomb
  A(cross section) = cross section between the two nodes
  d = distance of the center of mass of the two adjacent nodes

LOCATION	H/C TYPE	SKIN TYPE	SKIN Conduct. [W/mK]	SKIN THICK. [mm]	CORE Conduct. [W/mK]	CORE THICK. [mm]	K_{XY} [W/mK]	K_Z [W/mK]
Cylindrical structure Cone Structure Solar Array	3/16-7075-.0007	Al 7075	130	0.4	130	15	**7.06**	**1.34**

3.2.1.3 Unit - Panel conductivity

Calculation of linear conductors between units and panel is performed considering in general two contributions: the conduction due to the contact area, and the spreading effect; the last one is present when the mounting node area is bigger than contact area.
The linear conductor due to the contact area is evaluated by means of the formula:

$$GL = G_c * A_c \quad [W/°C] \qquad \textbf{(1)}$$

Where:

With filler

- for contact area between 30 and 1000 cm^2 :

  $G_c = 50000 * C_c^{-0.9}$ (C_c = contact area in cm^2)
  A_c = contact area in m^2

- for contact area bigger than 1000 cm^2 :

  $G_c = 100$
  A_c = contact area in m^2

Details of Unit–Panel contact conductance (including spreading effect if applicable) are given in the following table

UNIT	NODE	PANEL	CONTACT AREA [cm^2]	CONTACT TYPE	GL [W/K]
BATTERY	101	Int. Cylinder Struct.	169	Filler on Doubler	**6.634**
SRSE	102	Int. Cylinder Struct	205	Filler on Doubler	**6.764**
PGBE	103	Int. Cylinder Struct	425	Filler on Doubler	**7.275**
CDMU	104	Int. Cylinder Struct	1104	Filler on Doubler	**8.003**
TRSP2	105	Int. Cylinder Struct	437	Filler on Doubler	**7.295**
TRSP2	107	Int. Cylinder Struct	437	Filler on Doubler	**7.295**
RFDN	106	Int. Cylinder Struct	88	Filler on Doubler	**6.215**
PCU	108	Int. Cylinder Struct	930	Filler on Doubler	**7.867**

Thermal Doublers under each unit have been considered in Aluminium with a mean equivalent thickness of 2mm; in the following table the list of doublers for each unit is reported with the associated dimensions

Unit	Dimensions [m]	Area [m^2]
Battery	0.130 x 0130	0.0169
SRSE	0.108 x 0.190	0.0205
PGBE	0.170 x 0.250	0.0425
CDMU	0.460 x 0.240	0.1104
TRANSP 1	0.190 x 0.230	0.0437
TRANSP 2	0.190 x 0.230	0.0437
RFDN	0.080 x 0.110	0.0088
PCU	0.300 x 0.310	0.0930
Tot area [m^2]		**0.3795**

3.3 TCS temperature Requirement

The thermal requirements derive from the goal to maintain a thermal configuration able to perform the needed scientific measures. The high spin frequency value makes negligible the azimuthal temperature difference, while the axial effect shall be limited. Moreover it is important to maintain the temperature stable. The mechanical suspensions are sensitive to the temperature variation and this variation shall not degrade the common mode rejection of the mechanical suspension.

The temperature requirements to be guaranteed by the TCS are here reported:

- test mass mean temperature stability better than 0.1°C/day
- Axial temperature gradient at the level of the proof masses shall not exceed 1 °C/shaft length (previous value < 4 °C/m).
- Temperature fluctuations in the proof masses shall not exceed 0.2 °C in 1 day.
- Linear temperature drift in the proof masses shall not exceed 0.2 °C/day.

As for the electronic units, the following temperature requirements were assumed:

- -20/+50 °C operating temperature;
- -30/+60 °C non operating temperature.

3.4 GG - Orbit and Attitude data

The GG mission analysed is a circular equatorial orbit around the Earth with an altitude of 520km and an orbit inclination of 0°.
The satellite is spinned around its Z-axis at a rate of 1Hz and the attitude considered is with Z-axis (spin axis) normal to orbit plane.

The orbital cases analysed have been essentially selected through the variation of the environmental parameters and in particular:

- Sun Aspect Angle
- Solar Fluxes
- Albedo coefficient
- Earth emitted Infra Red

The Sun Aspect Angle considered is varying from 0° (spin axis normal to Sun direction) to 28.5°, which includes the typical Solar declination (23.5°) and the maximum pointing error on the satellite control estimated in 5°.

Solar Fluxes are computed considering the extreme values of Solar constant over the year, that correspond to 1315 W/m² at Summer Solstice, and 1420 W/m² at Winter Solstice.

Albedo and Earth IR have been assumed for a typical orbit inclination of 0°.

Spinning rotation has taken into account in flux computation, considering for each orbital position of the satellite the average on external heat input (Solar, Albedo and IR fluxes) over 12 different spin positions.

The list of orbital parameters used for the calculation of external heat fluxes is here reported:

Orbit and Attitude data

Orbit case	Cold Case Beginning of Life	Hot Case End of Life	Hot Case End of Life
Earth-Sun distance	152.1 E06 Km	149.6 E06 Km	149.6 E06 Km
Sun temperature	5770 K	5770 K	5770 K
Solar Aspect Angle	0°	0°	28.5°
Inclination	0°	0°	0°
Orbital altitude	520 Km	520 Km	520 Km
Orbital period	5699.35 s	5699.35 s	5699.35 s
Solar Constant	1315 W/m²	1420 W/m²	1420 W/m²
Earth albedo factor	0.18	0.28	0.28
Earth temperature	251 K	263 K	263 K
Attitude	+Z normal to orbit plane	+Z normal to orbit plane	+Z normal to orbit plane
Number of orbital positions	12	12	12
Spin rate	360 deg/s	360 deg/s	360 deg/s
Spin results averaged over	12 positions	12 positions	12 positions

In the following pictures the Solar heat flux distribution in EOL condition on two different attitude considered (SAA 0° and 28.5°) are represented. Planet and satellite are not in scale.

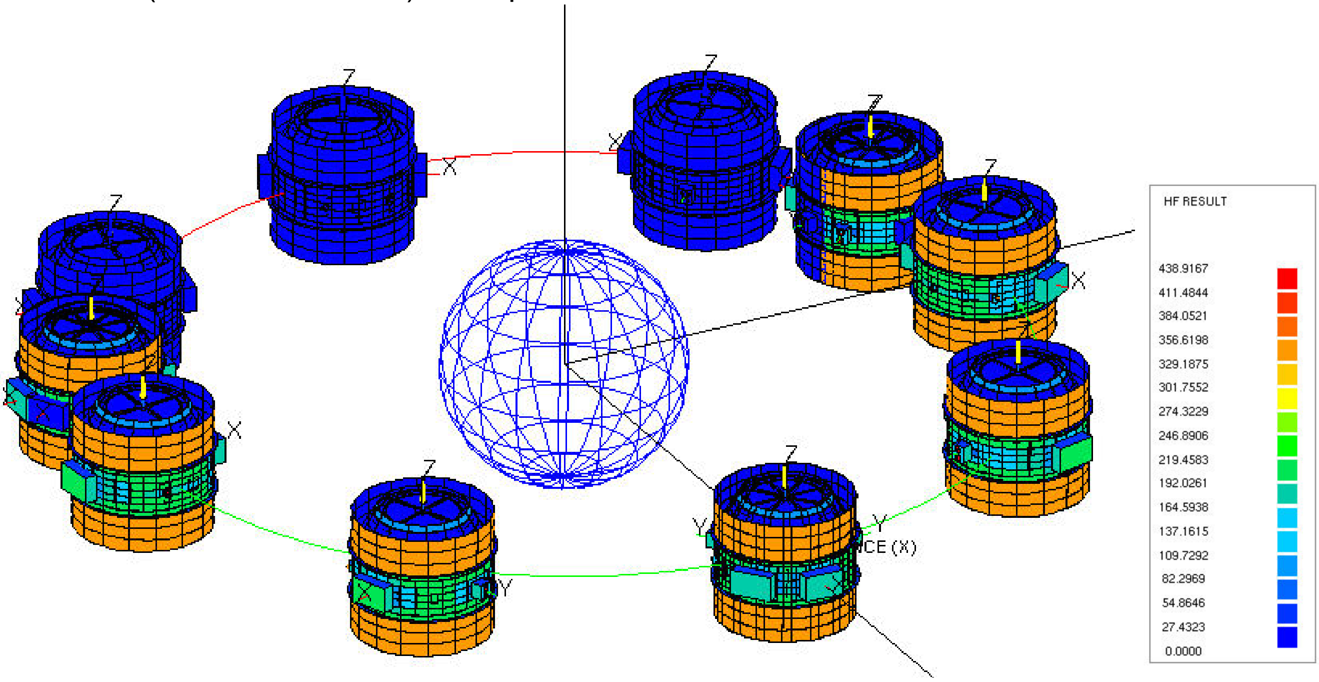


Figure 3.4-1 : Solar Heat flux distribution at SAA=0° (EOL)

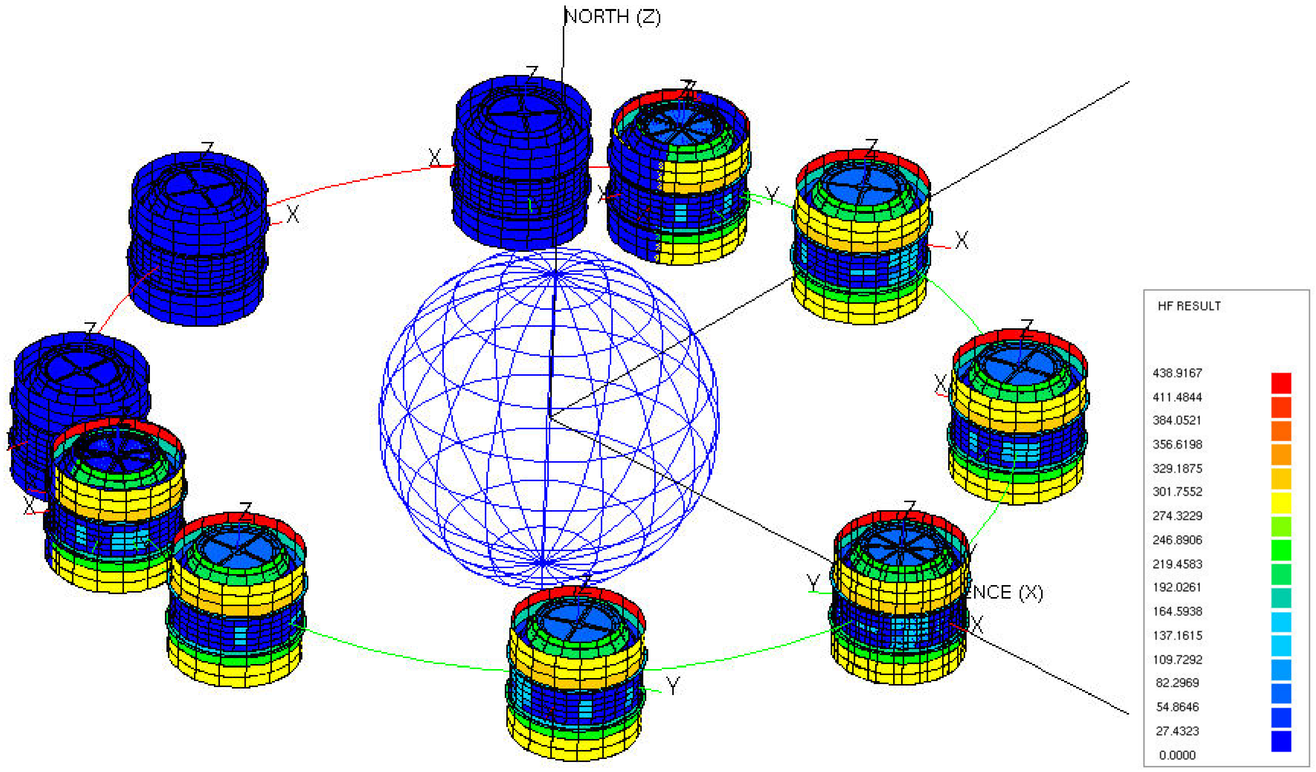


Figure 3.4-2 : Solar Heat flux distribution at SAA=28.5° (EOL)

3.5 GG - Unit Power dissipation

The Unit power dissipations considered for the thermal analysis take into account, for each orbit, the maximum value of power dissipation when the S/C is exposed to Sun fluxes, while the minimum value is considered during the eclipse phase.
The operating Transponder (TRSP2) in Sun Phase is maintained at 20W of dissipation for 10 minutes per orbit and then set at 6W of dissipation for remaining orbit duration.

A summary of the configuration used is given in the following table:

Node	Unit	Power in Sun	Power in Eclipse	Remarks
		[W]	[W]	
101	BATTERY	11	0	
102	SRS	1	0	
103	PGBE	23	0	
104	CDMU	45	14.4	
105	TRSP2	20 / 6 (1)	6	(1) 20W for 10min/orb 6W for 85min/orb
106	RFDN	0	0	
107	TRSP1	6	6	
108	PCU	55	14	
74000	EPSA1+PPCU+NEUTRAL	30	0	
75000	EPSA2+PPCU+NEUTRAL	30	0	
	ECE (2)	4	4	(2) Power assigned to internal PGB node (TMM node 4090)
	Total Power dissipation	**225 / 211**	**44.4**	

4. THERMAL ANALYSIS RESULTS

Thermal analysis cases have been performed identifying the sizing cases in accordance to environment parameters as described in paragraph 3.5 and satellite operating mode as reported in paragraph 3.4

The Hot case analysed to size the dimension of the radiators' area, has been computed considering the environment parameters with the Sun closest to the Earth (at Winter solstice) and Albedo and Earth radiation considered at their maximum values. In addition the thermo-optical properties of surfaces are at End of Life at their largest absorptivity.

The Cold case analysed to assess the heater power consumption needed to maintain the unit above their minimum operative limit, has been performed with Sun farthest from the Earth (at Summer Solstice), and Albedo and Earth radiation considered at their minimum values. Thermo-optical properties of surfaces are at Beginning of Life at their smallest absorptivity.

4.1 GG – Thermal cases analysed

Transient analysis have been performed in order to evaluate the temperature variations along a series of orbit cycles, (sun + eclipse phase) and provide evidence that all equipments temperature remain within temperature design ranges; moreover also stability criteria on test masses temperature fluctuations and gradients shall be guaranteed within defined temperature requirements as reported in paragraph 3.3

Two different main configurations have been considered for thermal cases, according to the finish of the PGB internal structure (support cylinders, flanges, shaft) and support to the cone, that have been considered respectively with a low emissivity finish ($\varepsilon \leq 0.05$) or a high emissivity value (Black Paint ε=0.88). The purpose is to assess how different thermal finish may affect the temperature stability and gradient requirements on internal masses; with a configuration considering low emissivity thermo-optical properties the PGB internal enclosure is highly isolated from the rest of the satellite, which is positive factor in terms of temperature stability on test masses regardless external environment variations, but on the other hand the high time constant of the PGB could lead to a very long time needed to reach a stable temperatures inside the PGB itself. In particular this condition could occur at the very beginning of the operative phase and anytime the satellite should recover its control from a failure case.

The following pictures show the PGB internal components that have been considered at different thermo-optical properties in the analysed cases:

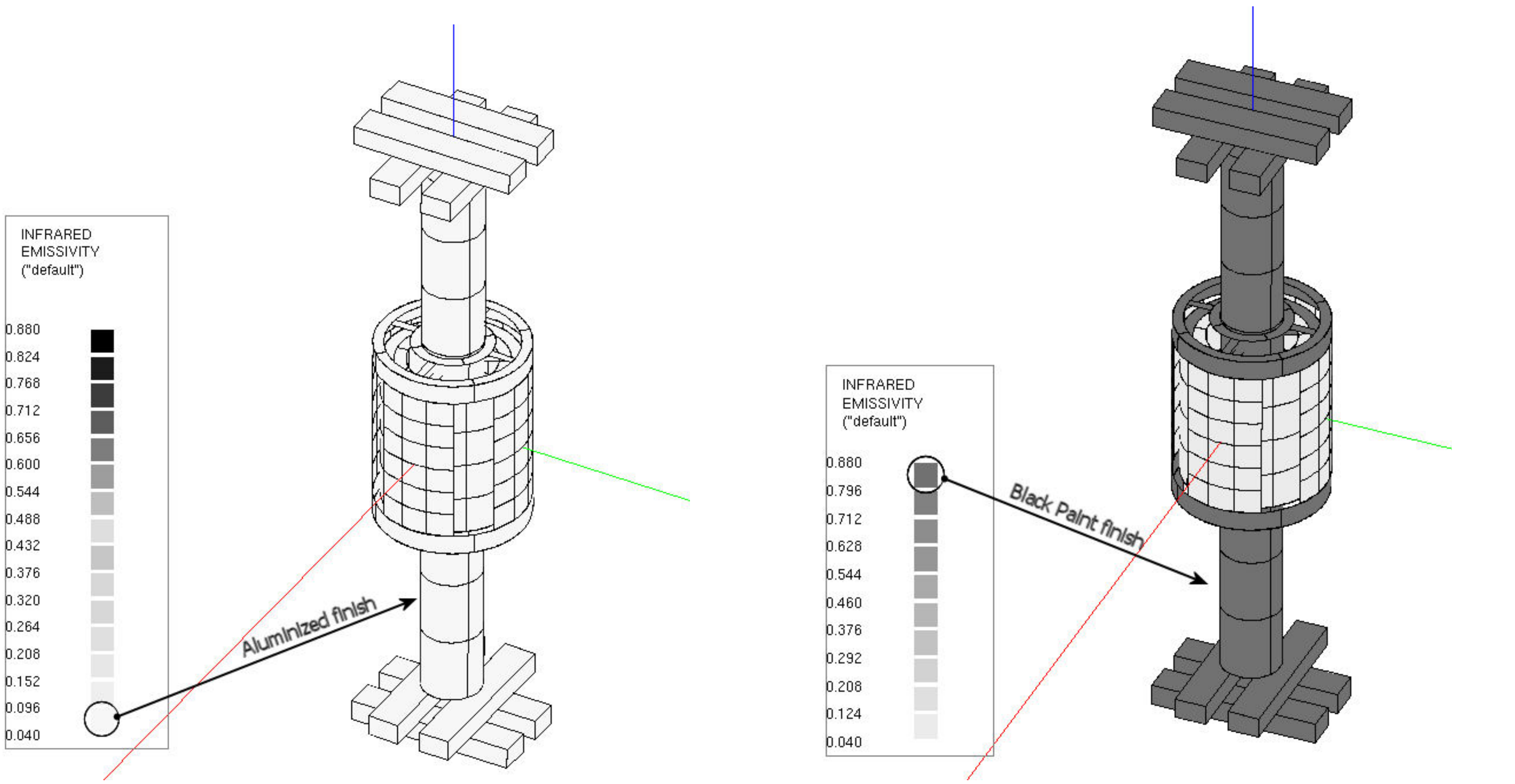


Figure 4.1-1: Internal PGB with Low Emissivity and Black Paint finish (M2 Mass and PGB MLI not displayed)

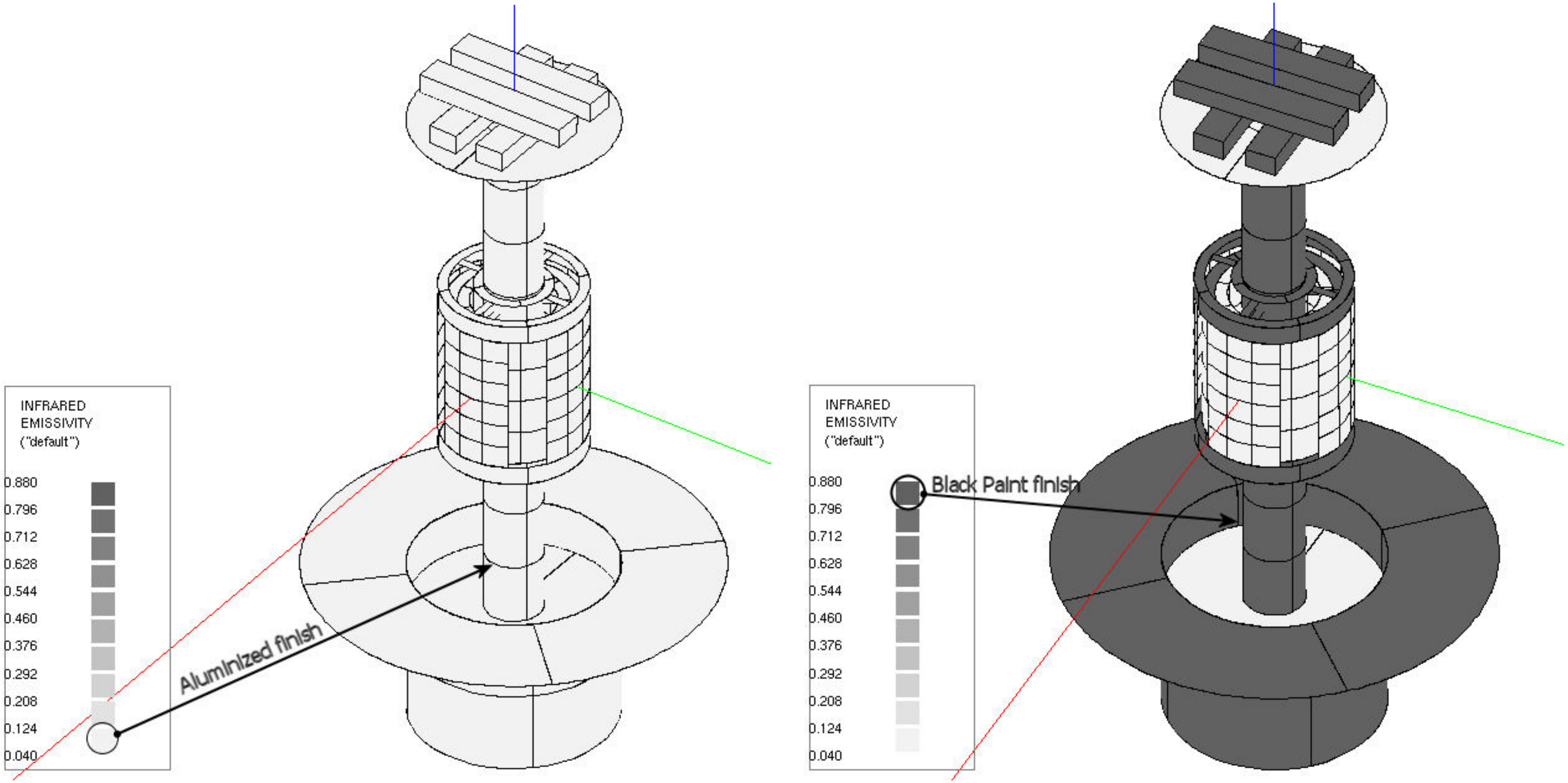


Figure 4.1-2: Internal PGB with Low Emissivity and Black Paint finish (M2 Mass and PGB MLI not displayed)

A summary of the analysis cases is given in the following table:

Case ID	Description	Remarks
1	BOL environment and thermo-optical properties – **SAA=0°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Low Emissivity finish (ε≤0.05)** Heater power applied on internal units	○ Heater sizing ○ Minimum temperature verification
2	EOL environment and thermo-optical properties – **SAA=0°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Low Emissivity finish (ε≤0.05)**	○ Radiators sizing ○ Maximum temperature verification
3	BOL environment and thermo-optical properties – **SAA=0°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Black Paint finish (ε=0.88)** Heater power applied on internal units	○ Heater sizing ○ Minimum temperature verification
4	EOL environment and thermo-optical properties – **SAA=0°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Black Paint finish (ε=0.88)**	○ Radiators sizing ○ Maximum temperature verification
		○
5	EOL environment and thermo-optical properties– **SAA=28.5°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Low Emissivity finish (ε≤0.05)**	○ Radiators sizing ○ Maximum temperature verification
6	EOL environment and thermo-optical properties– **SAA=28.5°** PGB MLI cover: Aluminium finish (ε=0.05) **PGB internal structure: Black Paint finish (ε=0.88)**	○ Radiators sizing ○ Maximum temperature verification

4.2 GG – Temperature analysis results

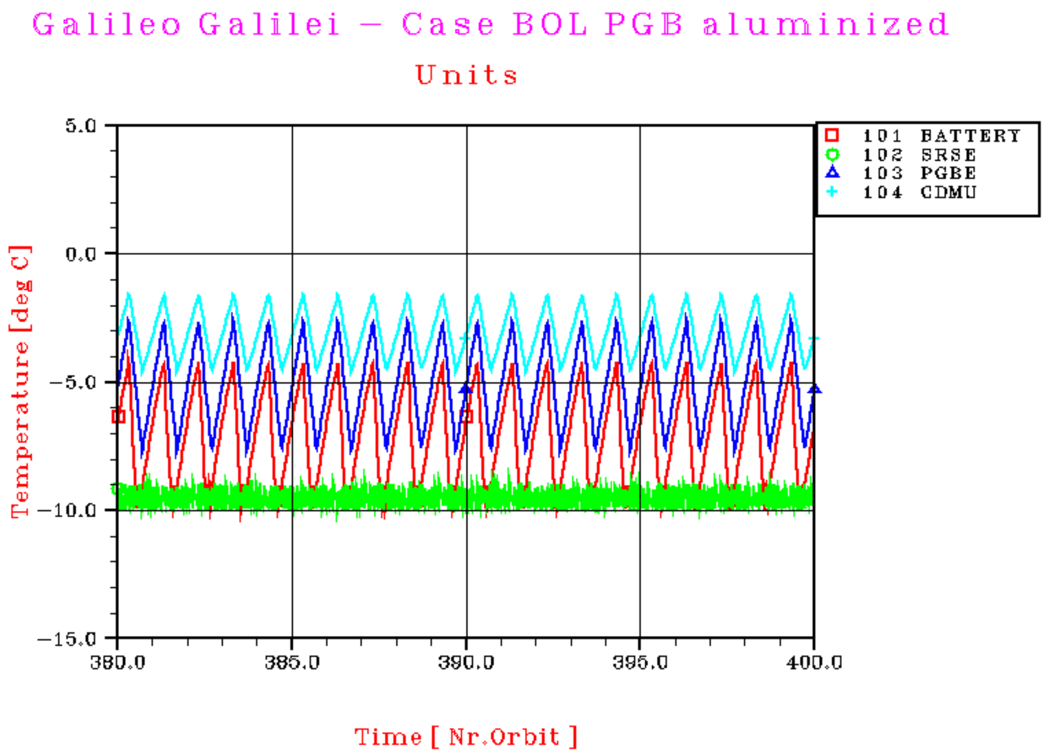
The temperature results for transient analysis performed, with PGB internal structure considered with low emissivity finish, are reported in the following table. The Table contains for the main items, the relevant TMM nodes, its description, the uncertainty applied, the temperature results in the transient analysis case, with the minimum values reported for the Cold cases and the maximum values reported for the Hot cases, the temperature with the relative uncertainty applied.
The temperature plots for Units and test masses are also presented to give evidence of the temperature range variation on a time period of 20 orbits.

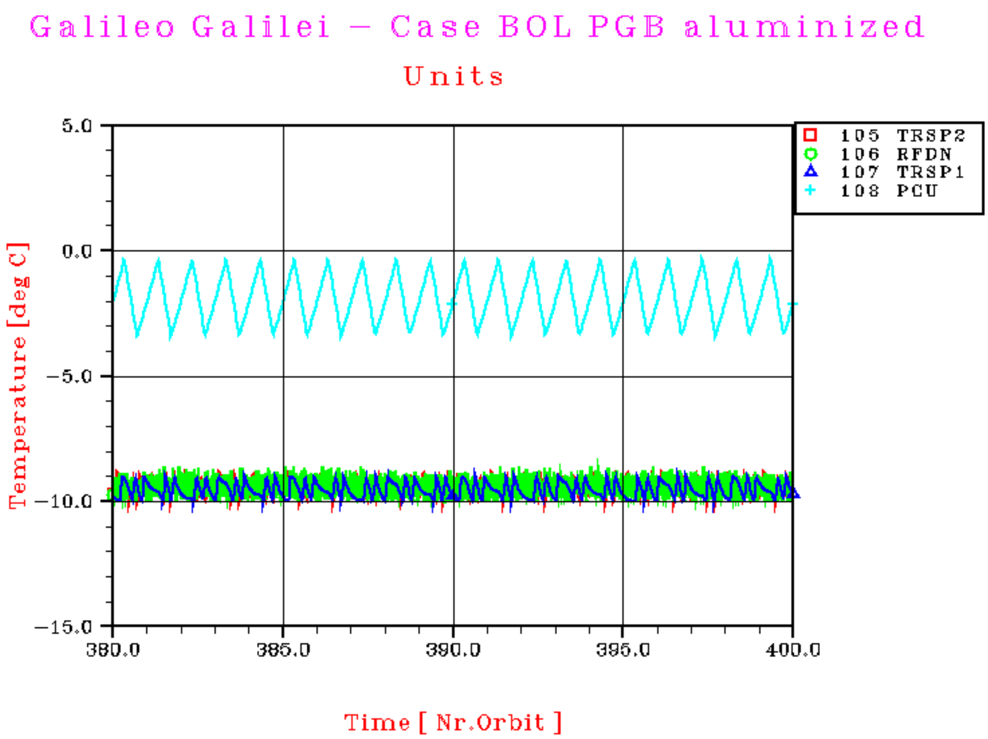
Case 1 & 2 – PGB internal structure aluminium finish Cold and Hot cases

			CASE 1			CASE 2						
			Cold Case	PGB ε≤0.05		Hot Case	PGB ε≤0.05		MIN	MAX	MIN	MAX
Node	Description	UFP	Tmin	Tmin-UFP		Tmax	Tmax+UFP		OPER.	OPER.	N.OP.	N.OP
		[°C]	[°C]	[°C]		[°C]	[°C]		[°C]	[°C]	[°C]	[°C]
101	Battery	10	-10.0	**-20.0**		9.6	**19.6**		-20	50	-30	60
102	SRSE	10	-10.0	**-20.0**		1.6	**11.6**		-20	50	-30	60
103	PGBE	10	-7.6	**-17.6**		11.4	**21.4**		-20	50	-30	60
104	CDMU	10	-4.5	**-14.5**		12.5	**22.5**		-20	50	-30	60
105	TRSP2	10	-10.0	**-20.0**		3.2	**13.2**		-20	50	-30	60
106	RFDN	10	-10.0	**-20.0**		0.3	**10.3**		-20	50	-30	60
107	TRSP1	10	-10.0	**-20.0**		2.2	**12.2**		-20	50	-30	60
108	PCU	10	-3.4	**-13.4**		13.5	**23.5**		-20	50	-30	60
4090	ECE inside PGB	10	16.7	**6.7**		27.3	**37.3**					
72000	Tank1	10	-14.2	**-24.2**		0.9	**10.9**					
72100	Tank2	10	-15.9	**-25.9**		0.0	**10.0**					
70000	Antenna +Z	10	-34.4	**-44.4**		-9.4	**0.6**					
70100	Antenna +Z	10	-58.7	**-68.7**		27.2	**37.2**					
71000	Antenna -Z	10	-34.7	**-44.7**		-9.6	**0.4**					
71100	Antenna -Z	10	-59.0	**-69.0**		27.1	**37.1**					
73110	ESS sensor	10	-6.5	**-16.5**		22.4	**32.4**					
73120	ESS sensor	10	-6.6	**-16.6**		22.6	**32.6**					
73210	CSS sensor	10	-4.4	**-14.4**		19.9	**29.9**					
73310	SRS sensor	10	-1.5	**-11.5**		21.3	**31.3**					
74000	EPSA 1	10	-44.3	**-54.3**		24.8	**34.8**					
75000	EPSA 2	10	-45.3	**-55.3**		24.8	**34.8**					
Tavg	M1 Mass	10	2.4	**-7.6**		14.1	**24.1**					
Tavg	M2 Mass	10	1.4	**-8.6**		13.2	**23.2**					
Tavg	Capacitive Plate1	10	2.36	**-7.7**		14.0	**24.0**					
Tavg	Capacitive Plate2	10	2.3	**-7.7**		14.0	**24.0**					
Tavg	Capacitive Plate3	10	2.3	**-7.7**		14.0	**24.0**					
Tavg	Capacitive Plate4	10	2.3	**-7.7**		14.0	**24.0**					

			CASE 1			CASE 2						
			Cold Case	PGB ε≤0.05		Hot Case	PGB ε≤0.05		MIN	MAX	MIN	MAX
Node	Description	UFP	Tmin	Tmin-UFP		Tmax	Tmax+UFP		OPER.	OPER.	N.OP.	N.OP
		[°C]	[°C]	[°C]		[°C]	[°C]		[°C]	[°C]	[°C]	[°C]
Tavg	Upper Shaft	10	13.5	**3.5**		24.1	**34.1**					
Tavg	Lower Shaft	10	-6.8	**-16.8**		5.9	**15.9**					

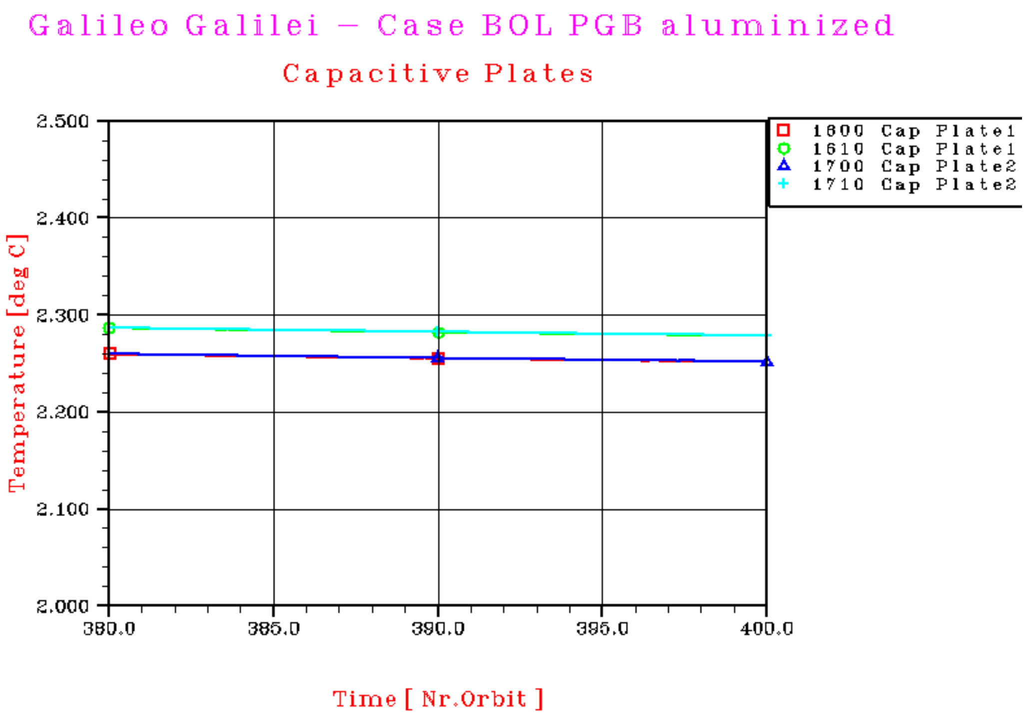
Figure 4.2-1: CASE1 – Cold case PGB aluminized – Units temperature





THALES

Figure 4.2-2: CASE1 – Cold case PGB aluminized – Capacitive Plates



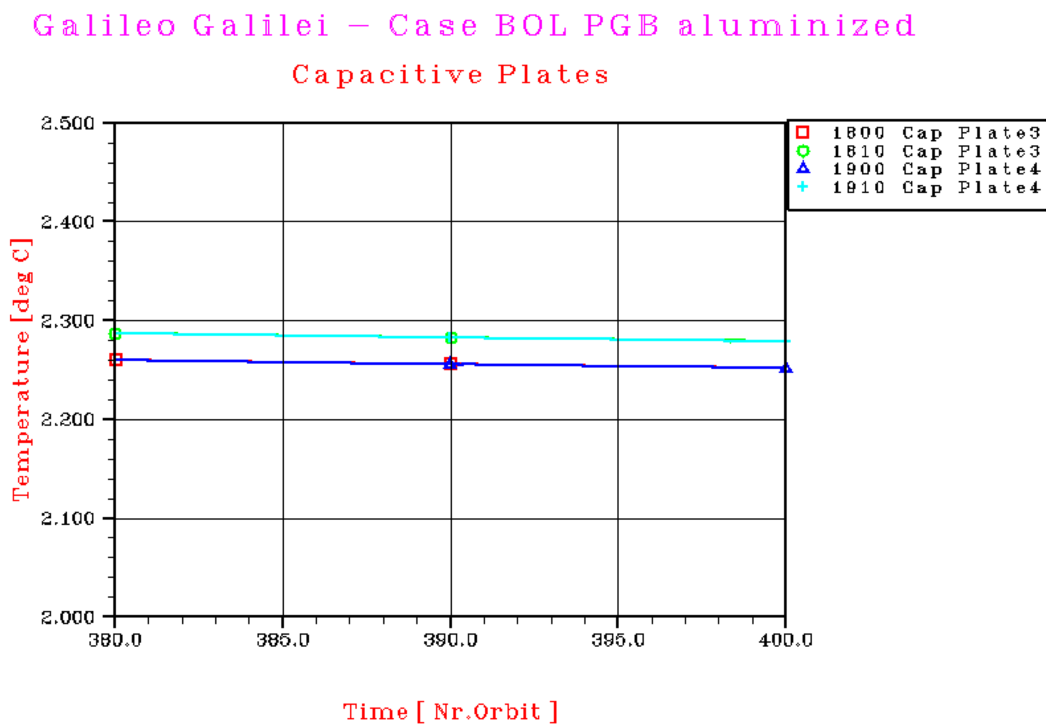
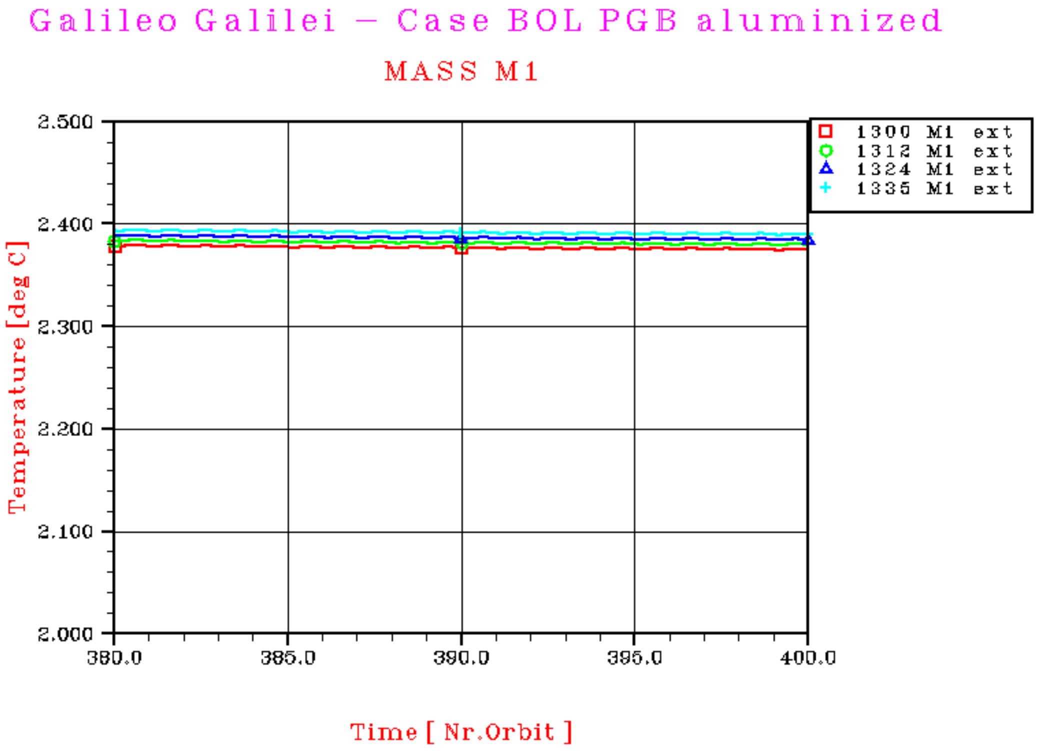


Figure 4.2-3: CASE1 – Cold case PGB aluminized – Mass temperature



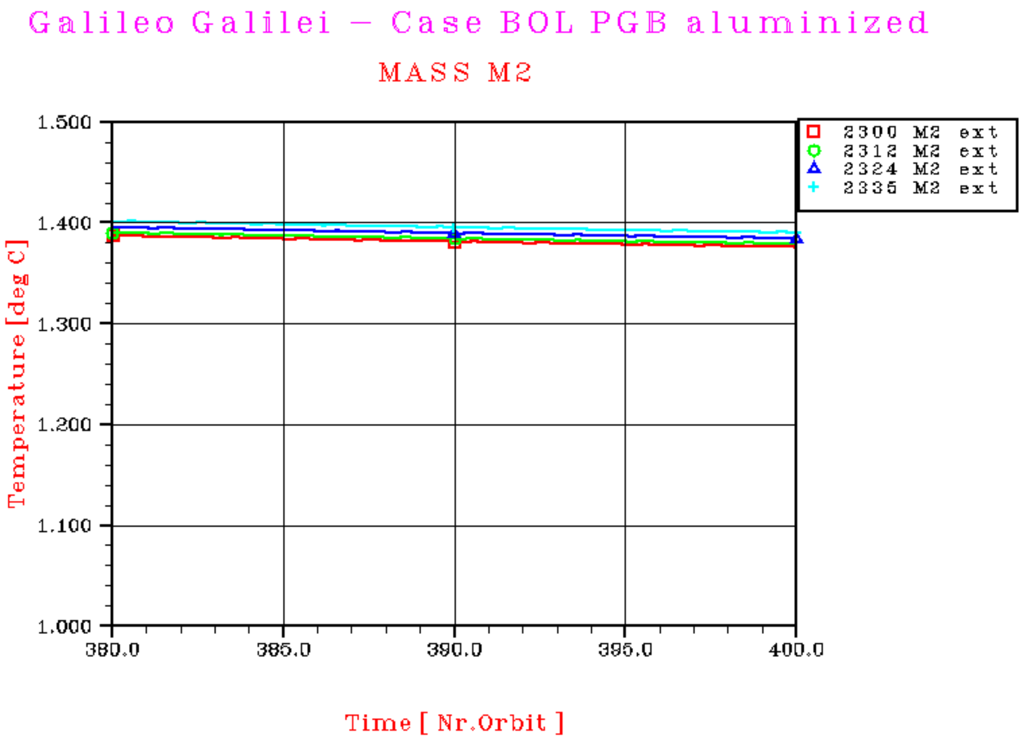
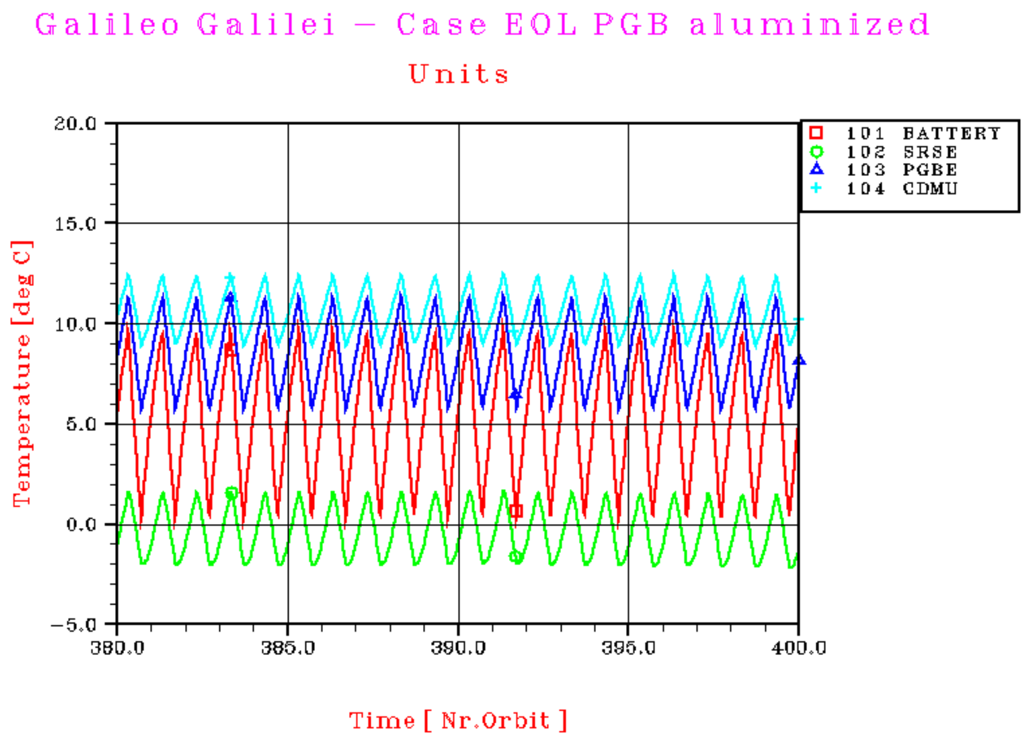


Figure 4.2-4: CASE2 – Hot case PGB aluminized – Units temperature



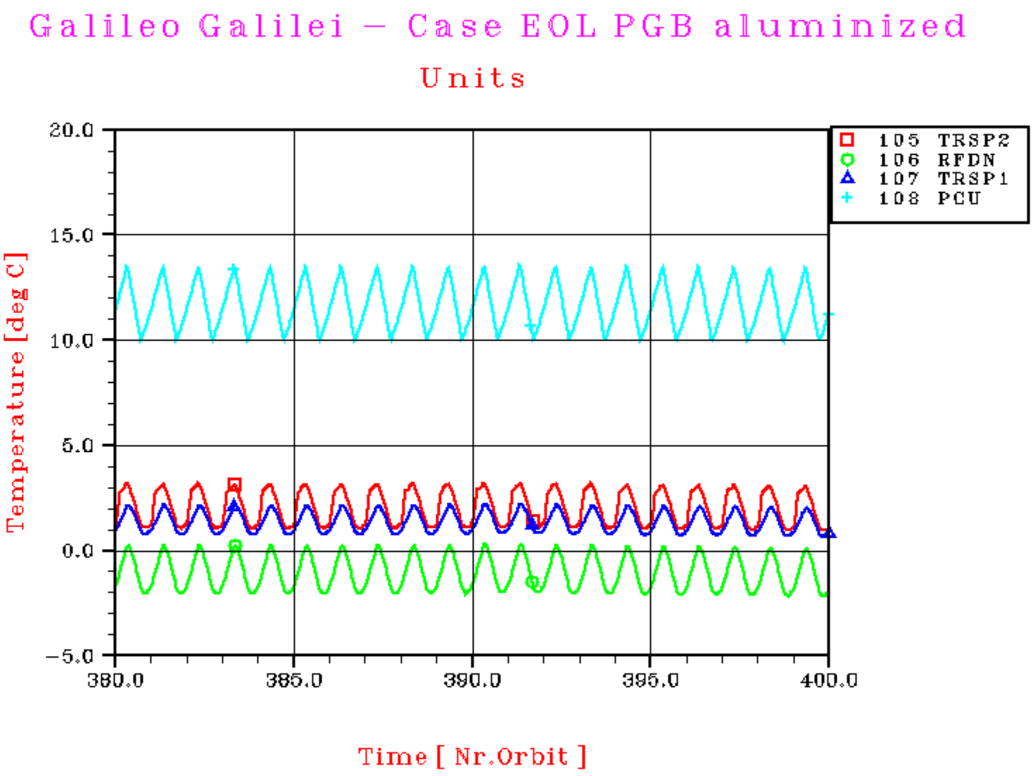
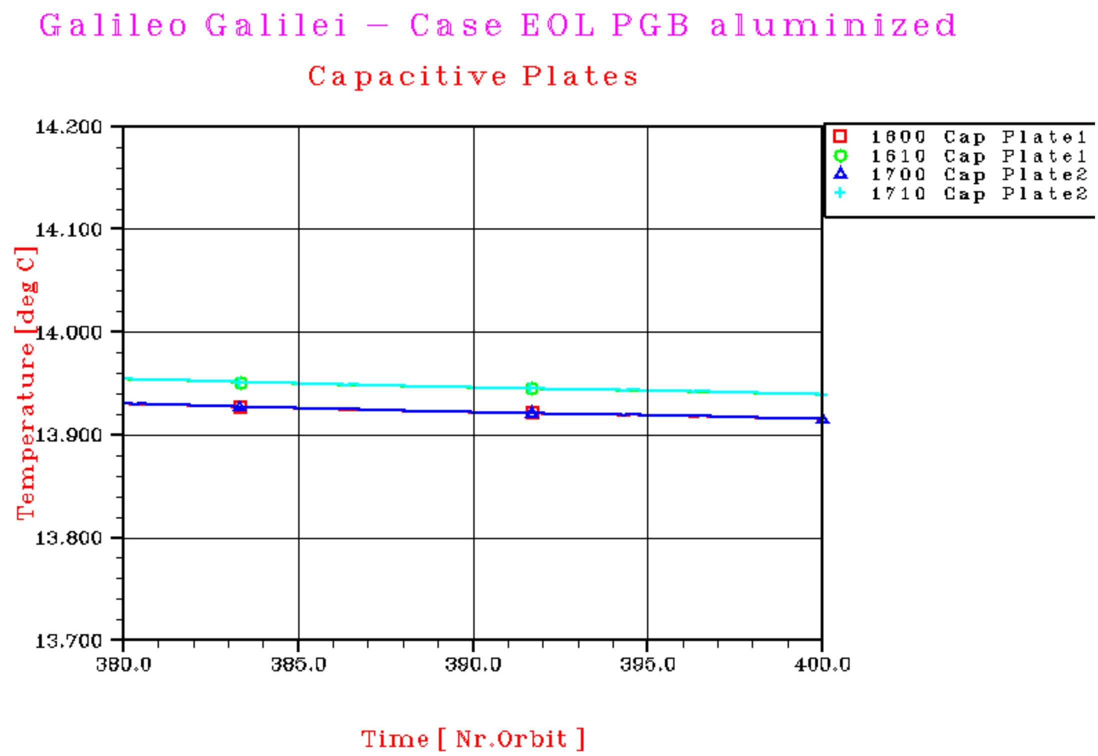


Figure 4.2-5: CASE2 – Hot case PGB aluminized – Capacitive Plates



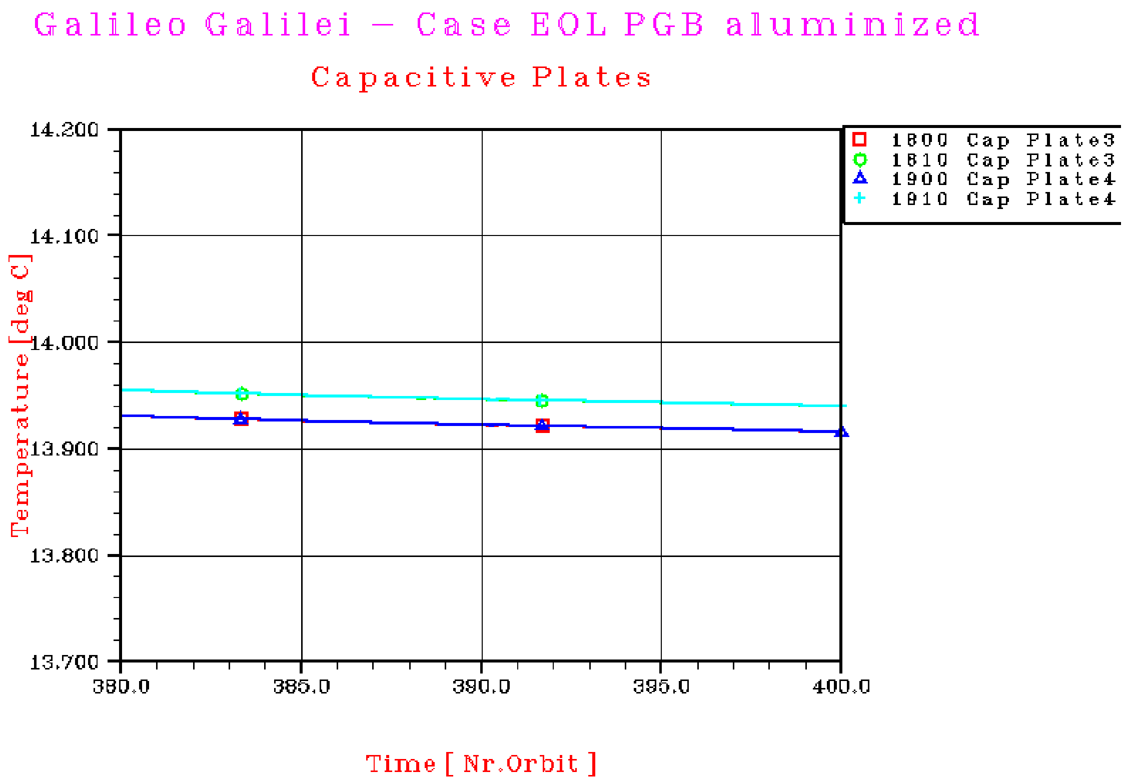
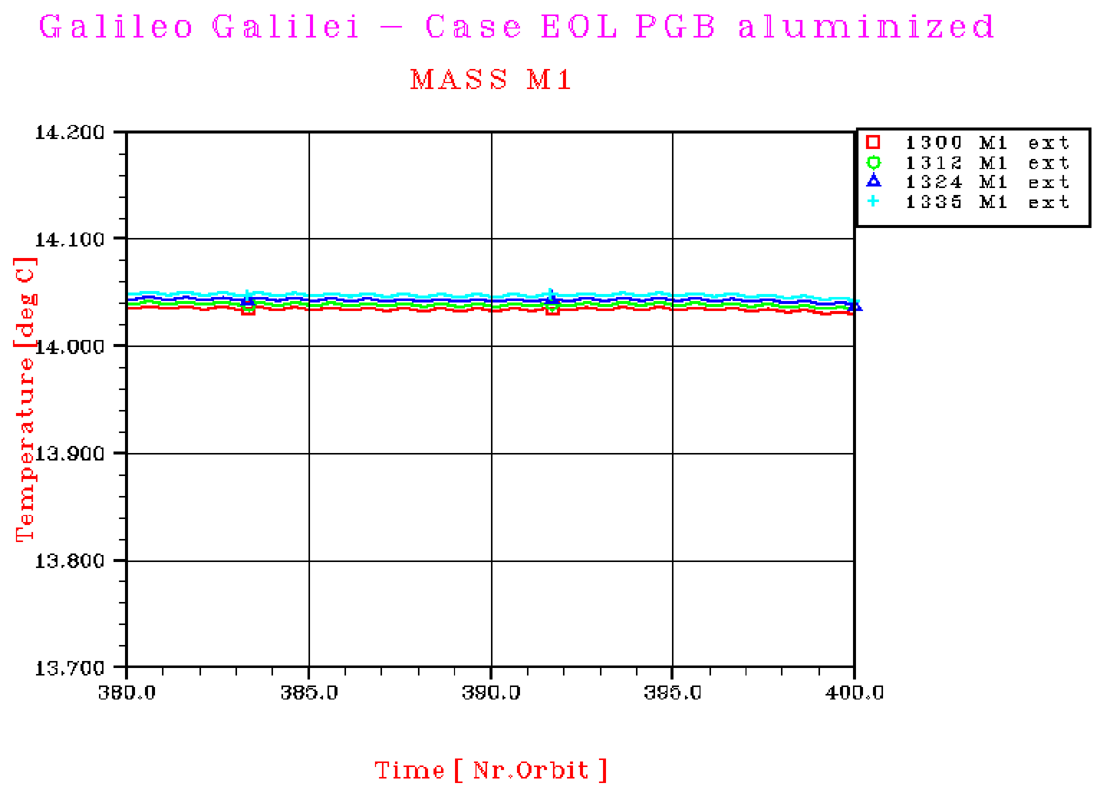
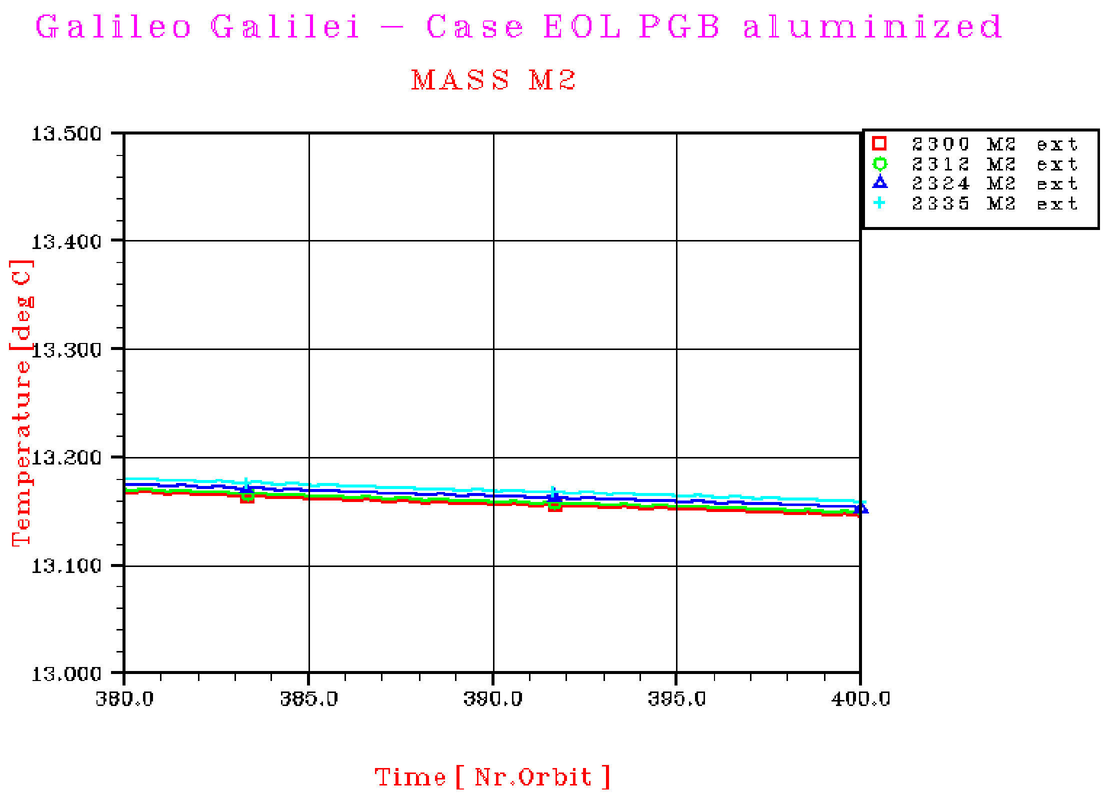


Figure 4.2-6: CASE2 – Hot case PGB aluminized – Mass temperature



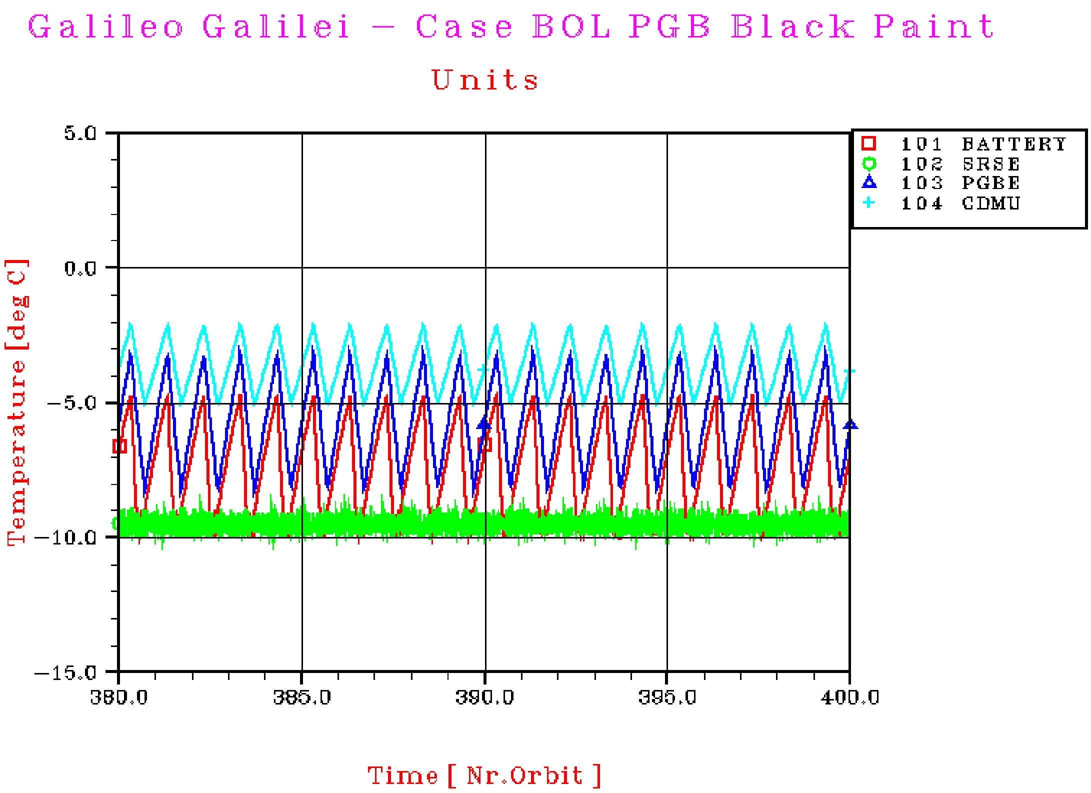


The temperature results for transient analysis performed, with PGB internal structure considered with high emissivity finish, are reported in the following table.

Case 3 & 4 – PGB internal structure Black Paint finish Cold and Hot cases

			CASE 3			CASE 4						
			Cold Case	PGB ε=0.88		Hot Case	PGB ε=0.88		MIN	MAX	MIN	MAX
Node	Description	UFP	Tmin	Tmin-UFP		Tmax	Tmax+UFP		OPER.	OPER.	N.OP.	N.OP
		[°C]	[°C]	[°C]		[°C]	[°C]		[°C]	[°C]	[°C]	[°C]
101	Battery	10	-10.0	**-20.0**		8.9	**18.9**		-20	50	-30	60
102	SRSE	10	-10.0	**-20.0**		0.9	**10.9**		-20	50	-30	60
103	PGBE	10	-8.2	**-18.2**		10.7	**20.7**		-20	50	-30	60
104	CDMU	10	-5.1	**-15.1**		11.8	**21.8**		-20	50	-30	60
105	TRSP2	10	-10.0	**-20.0**		2.6	**12.6**		-20	50	-30	60
106	RFDN	10	-10.0	**-20.0**		-0.4	**9.6**		-20	50	-30	60
107	TRSP1	10	-10.0	**-20.0**		1.6	**11.6**		-20	50	-30	60
108	PCU	10	-3.9	**-13.9**		12.9	**22.9**		-20	50	-30	60
4090	ECE inside PGB	10	-12.8	**-22.8**		1.2	**11.2**					
72000	Tank1	10	-14.7	**-24.7**		0.2	**10.2**					
72100	Tank2	10	-16.5	**-26.5**		-0.7	**9.3**					
70000	Antenna +Z	10	-31.5	**-41.5**		-6.7	**3.3**					
70100	Antenna +Z	10	-58.3	**-68.3**		27.7	**37.7**					
71000	Antenna -Z	10	-31.8	**-41.8**		-7.1	**2.9**					
71100	Antenna -Z	10	-58.5	**-68.5**		27.4	**37.4**					
73110	ESS sensor	10	-6.6	**-16.6**		22.4	**32.4**					
73120	ESS sensor	10	-6.6	**-16.6**		22.5	**32.5**					
73210	CSS sensor	10	-4.6	**-14.6**		19.8	**29.8**					
73310	SRS sensor	10	-1.5	**-11.5**		21.1	**31.1**					
74000	EPSA 1	10	-44.3	**-54.3**		24.8	**34.8**					
75000	EPSA 2	10	-45.4	**-55.4**		24.6	**34.6**					
Tavg	M1 Mass	10	-15.5	**-25.5**		-1.7	**8.4**					
Tavg	M2 Mass	10	-15.5	**-25.5**		-1.7	**8.3**					
Tavg	Capacitive Plate1	10	-15.5	**-25.5**		-1.6	**8.4**					
Tavg	Capacitive Plate2	10	-15.5	**-25.5**		-1.6	**8.4**					
Tavg	Capacitive Plate3	10	-15.5	**-25.5**		-1.6	**8.4**					
Tavg	Capacitive Plate4	10	-15.5	**-25.5**		-1.6	**8.4**					
Tavg	Upper Shaft	10	-14.0	**-24.0**		-0.3	**9.7**					
Tavg	Lower Shaft	10	-16.9	**-26.9**		-2.8	**7.2**					

Figure 4.2-7: CASE3 – Cold case PGB black paint – Units temperature



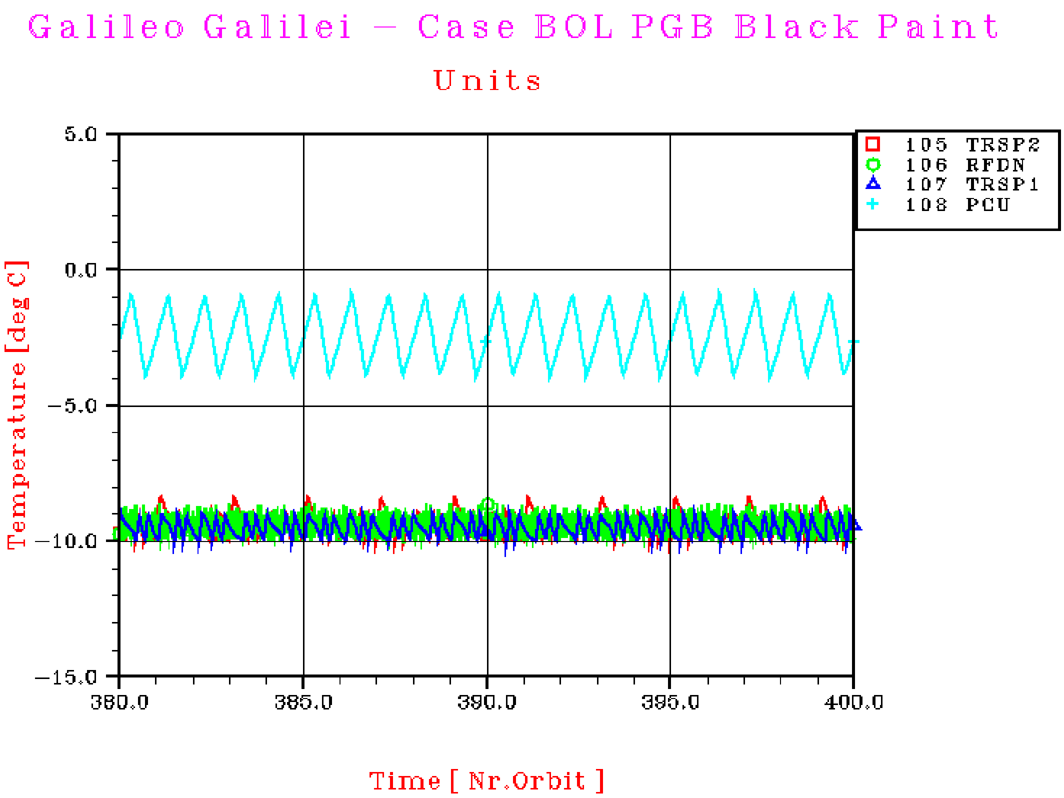
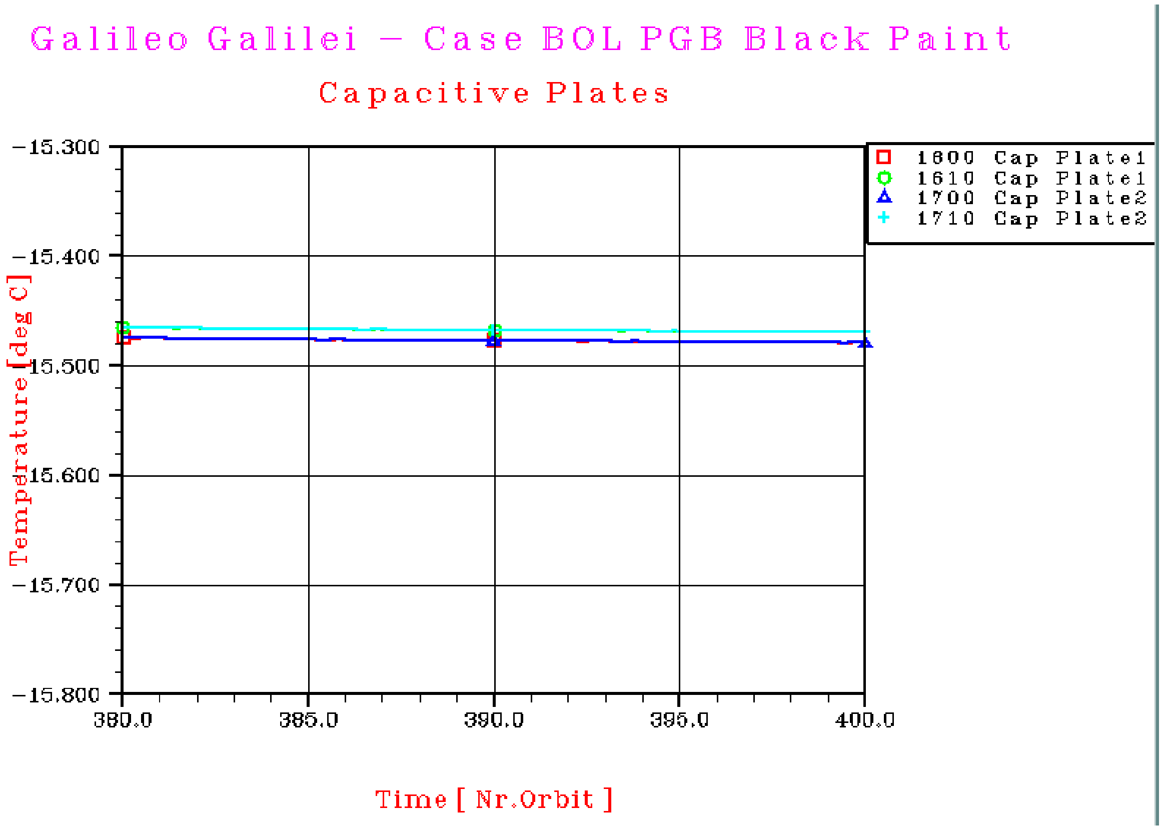


Figure 4.2-8: CASE3 – Cold case PGB black paint – Capacitive Plates



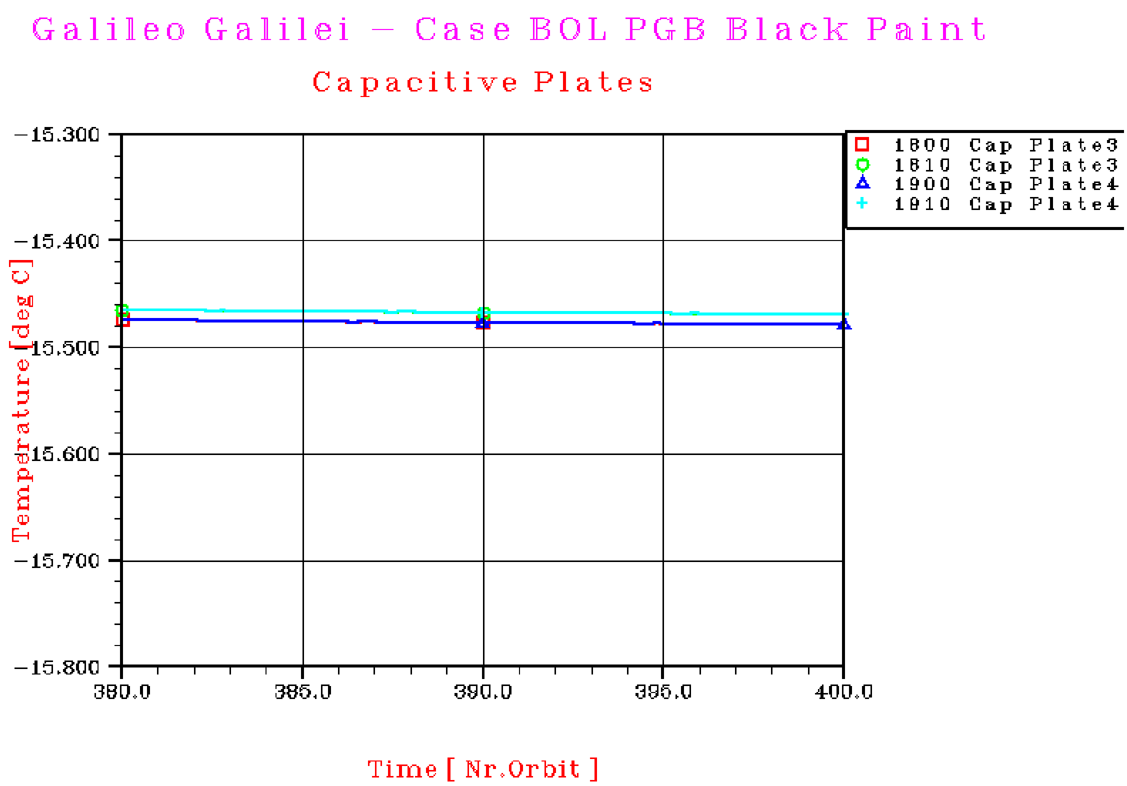
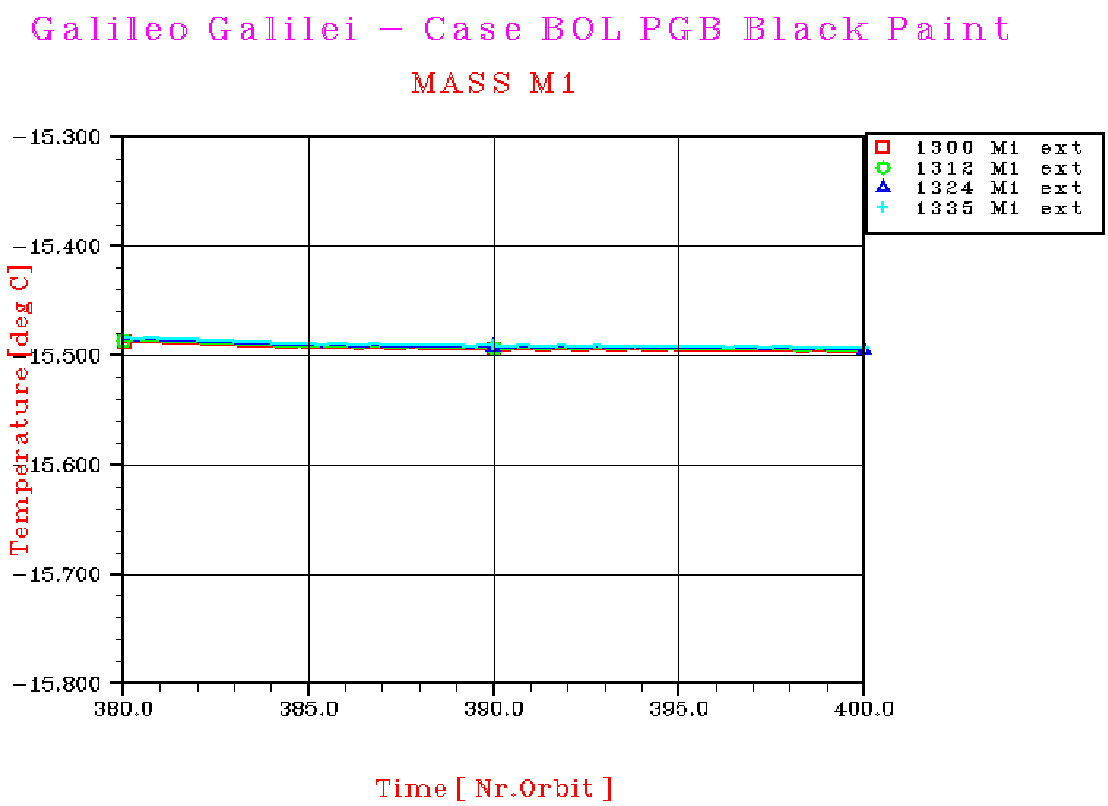


Figure 4.2-9: CASE3 – Cold case PGB black paint – Mass temperature



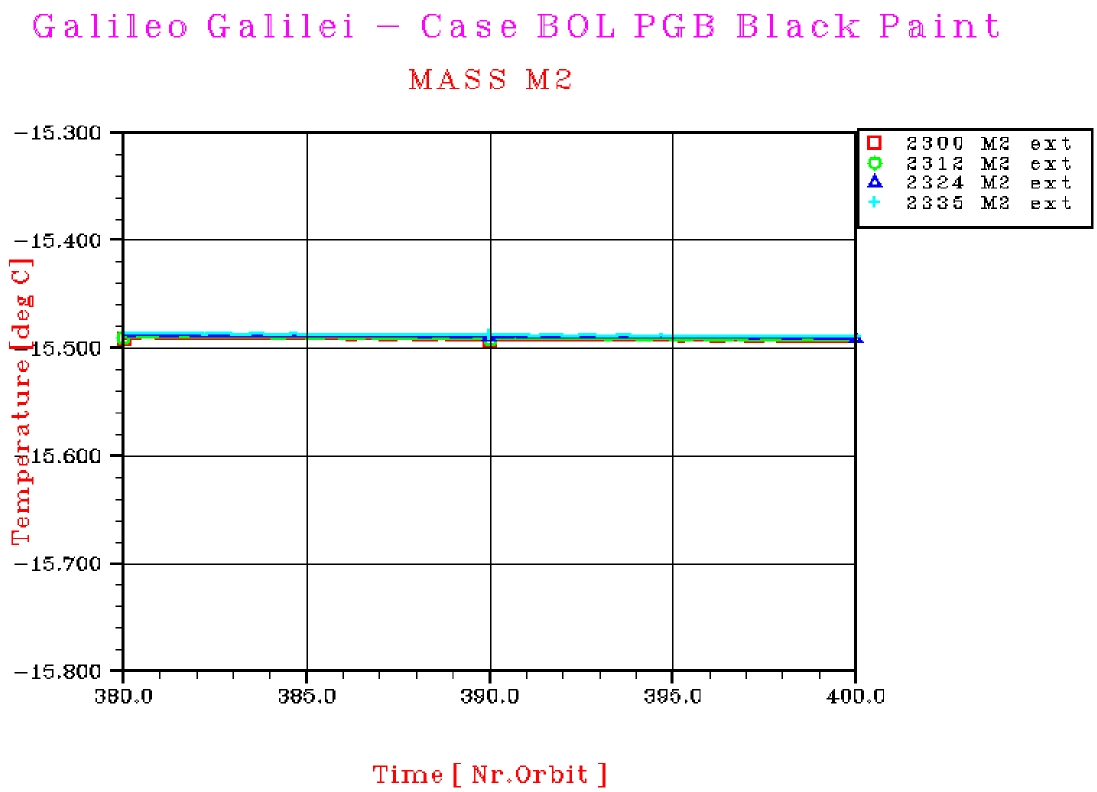
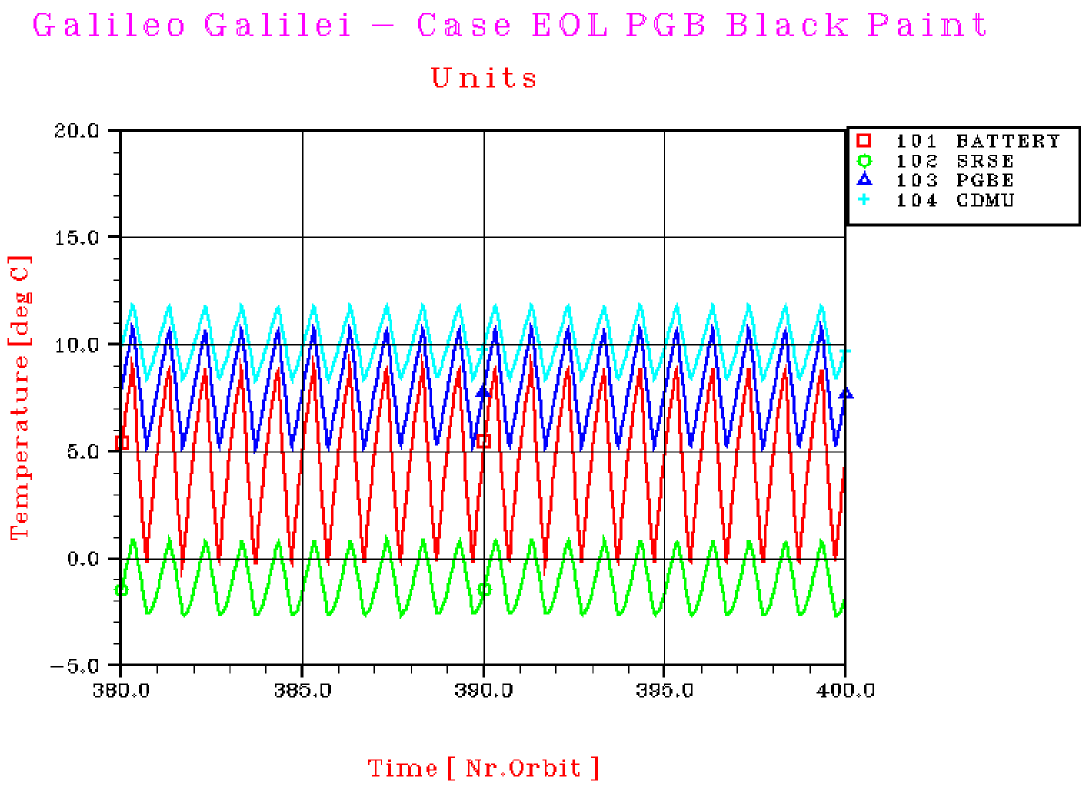


Figure 4.2-10: CASE4 – Hot case PGB black paint – Units temperature



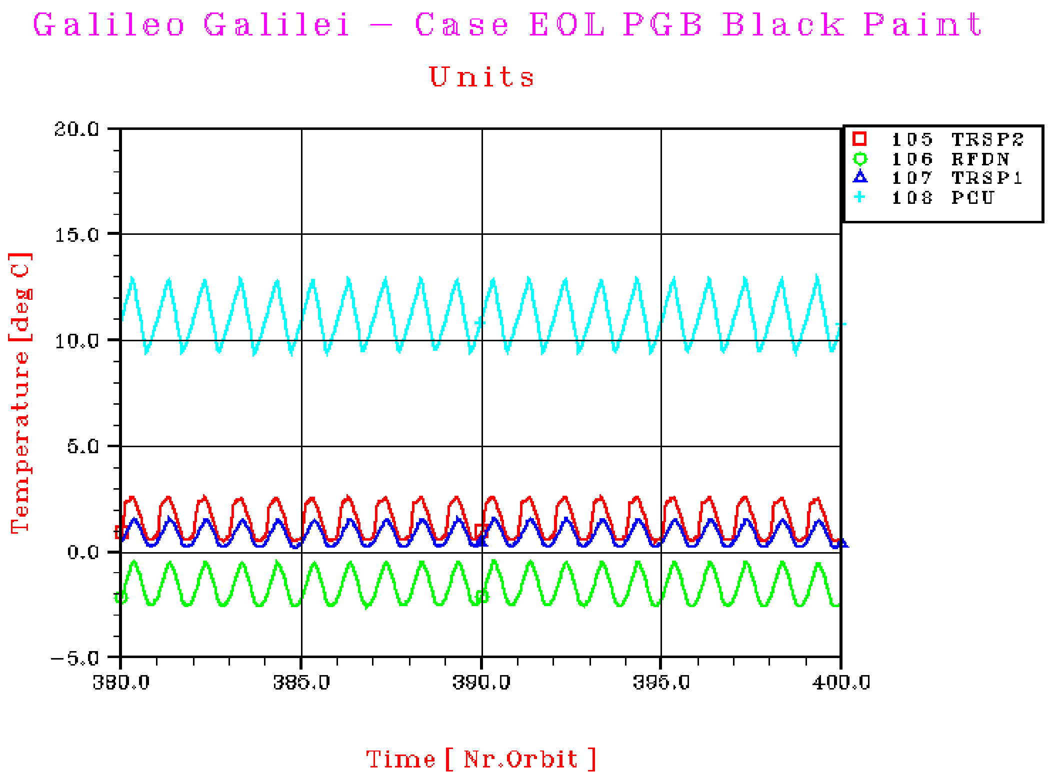
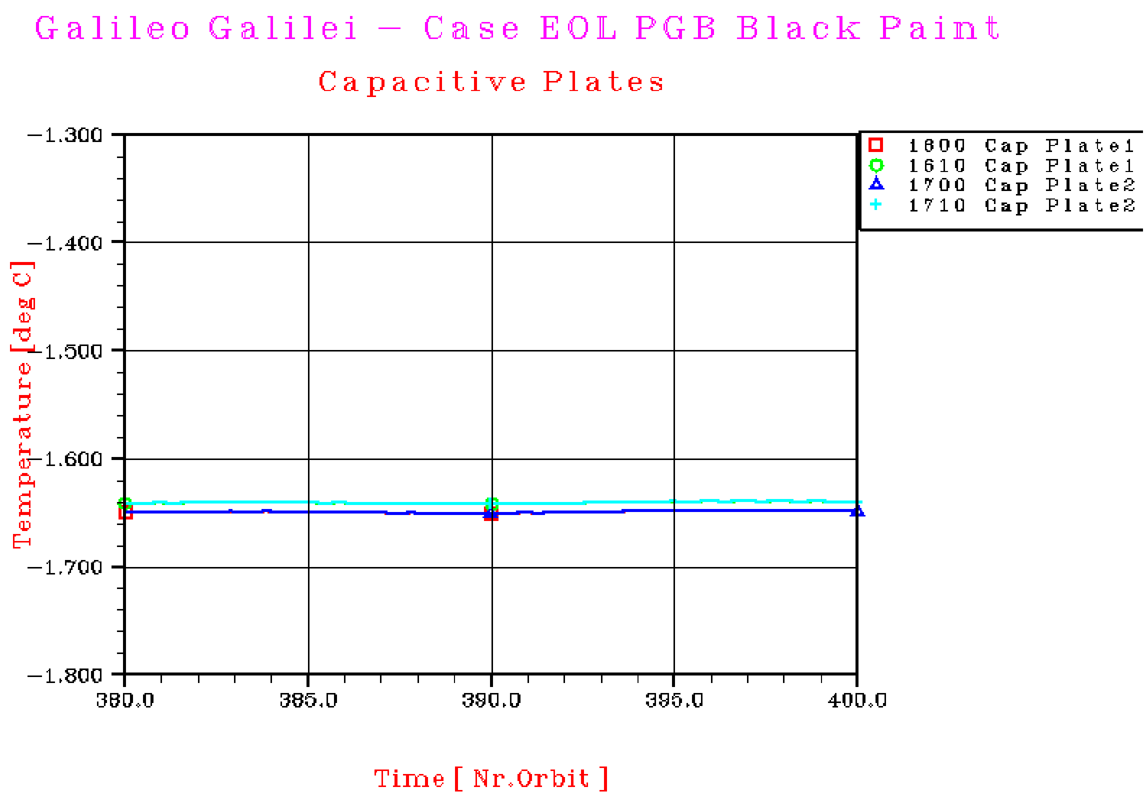


Figure 4.2-11: CASE4 – Hot case PGB black paint – Capacitive Plates



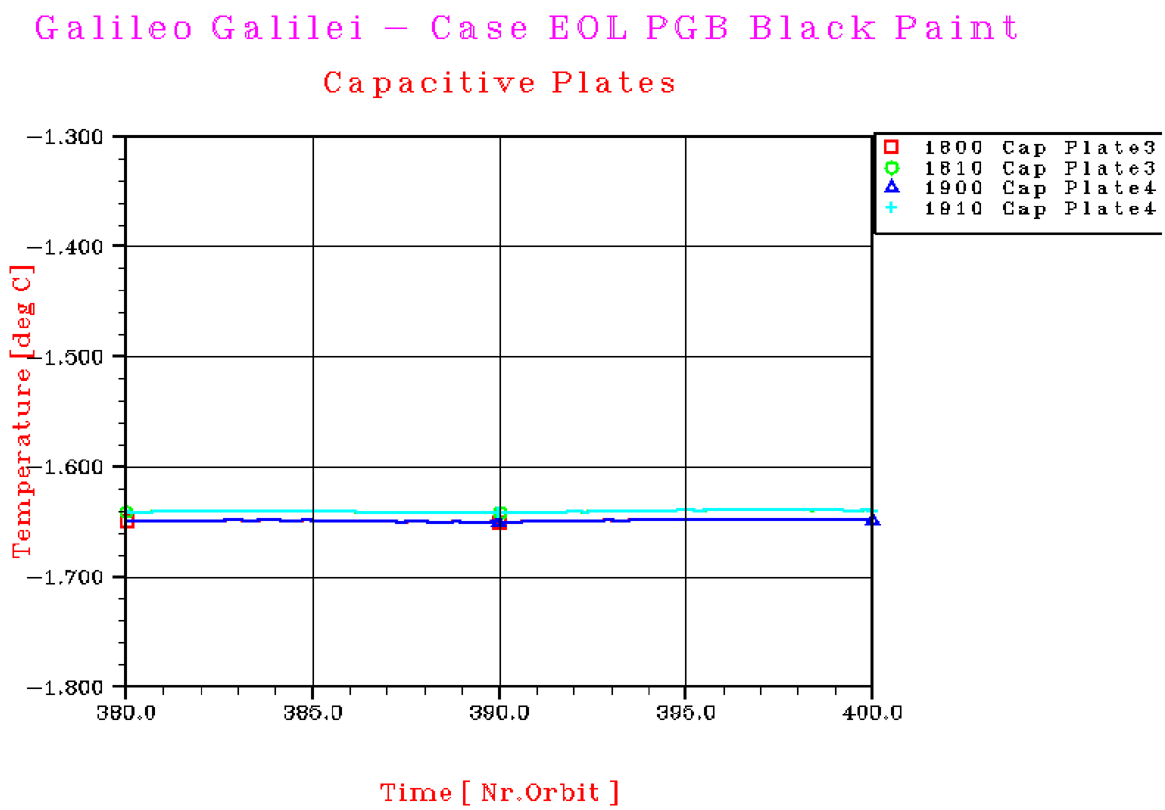
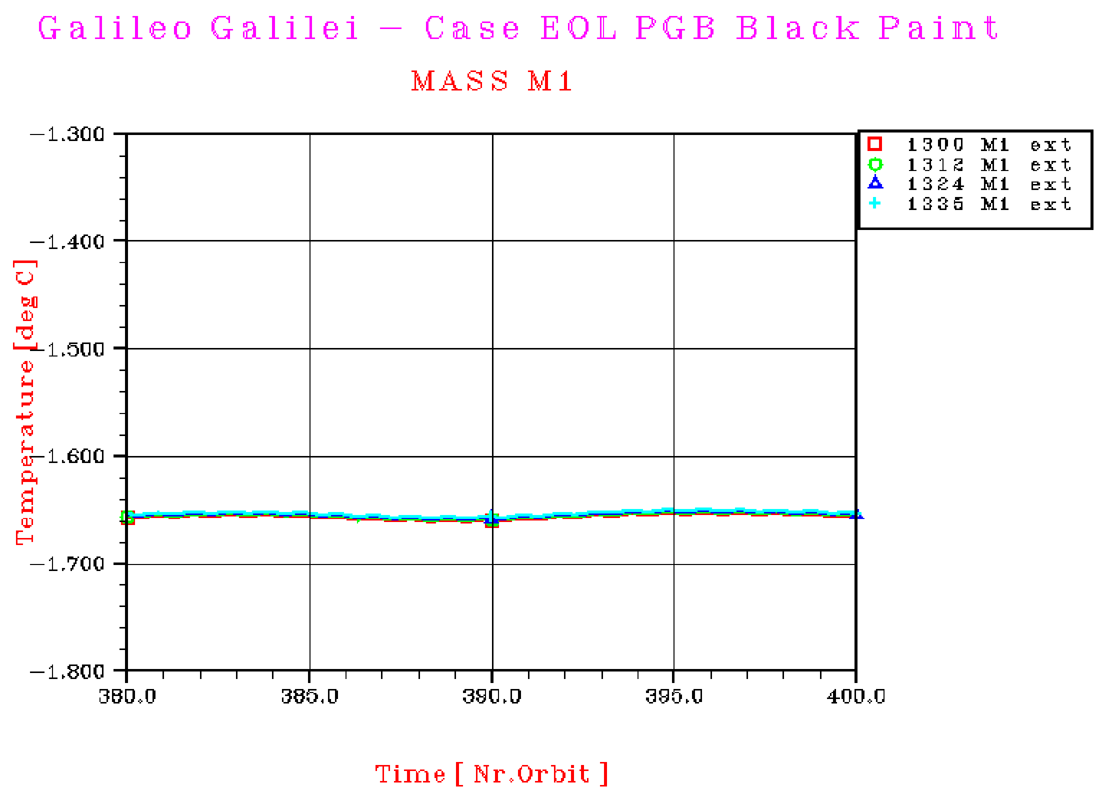
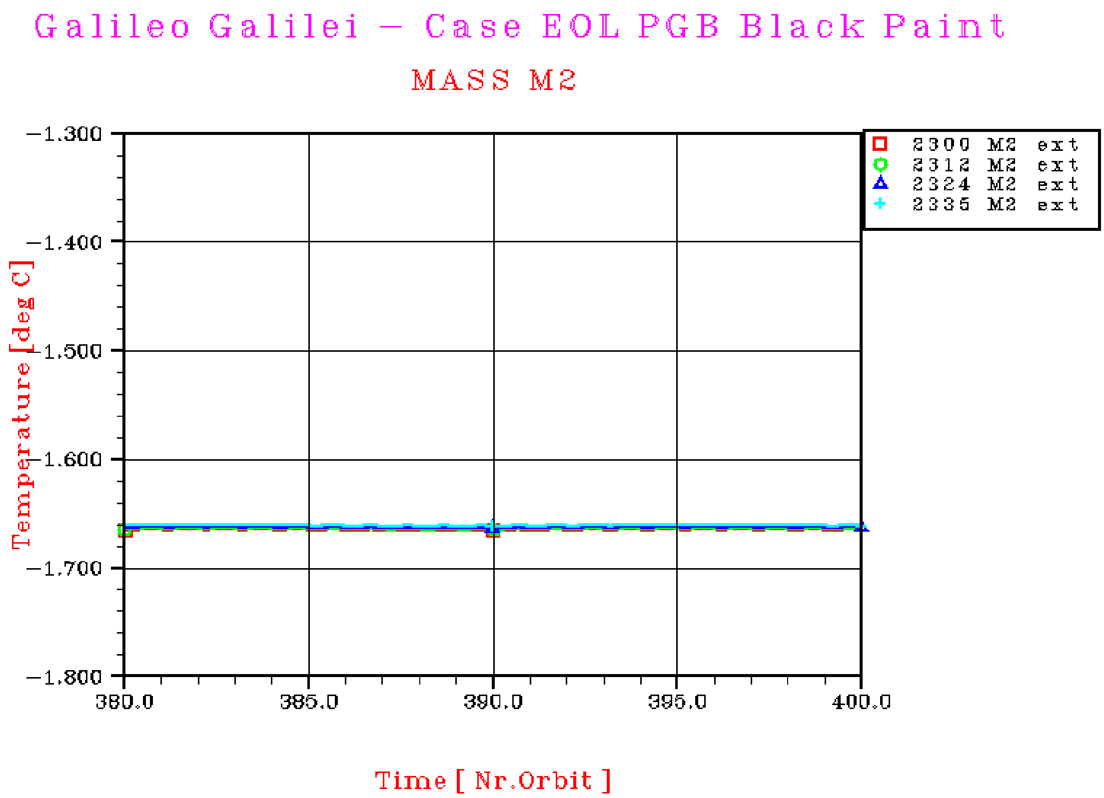


Figure 4.2-12: CASE4 – Hot case PGB black paint – Units temperature



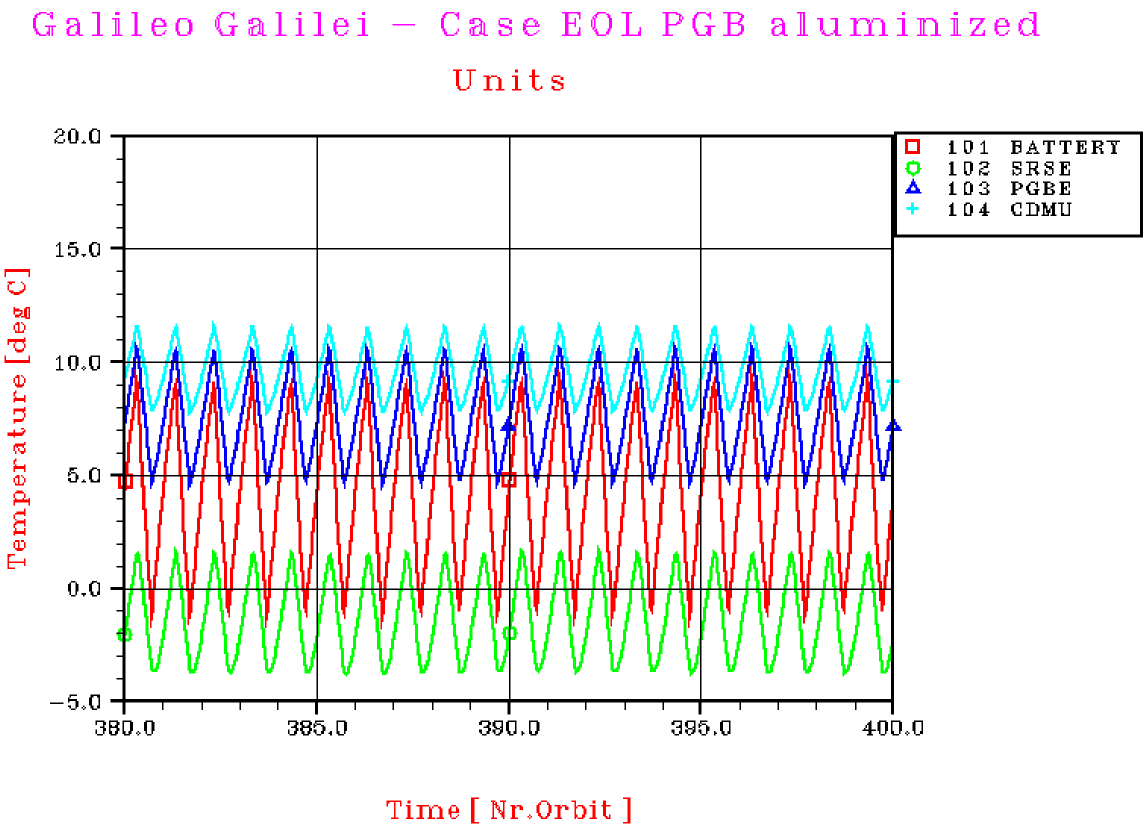


The temperature results for transient analysis performed, with a Solar Aspect Angle of 28.5° are reported in the following table.

Case 5 & 6 – Hot cases at SAA=28.5° with PGB internal structure in Aluminium or Black Paint finish

			CASE 5			CASE 6						
			Hot Case	PGB ε≤0.05		Hot Case	PGB ε=0.88		MIN	MAX	MIN	MAX
Node	Description	UFP	Tmax	Tmax+UFP		Tmax	T+UFP		OPER.	OPER.	N.OP.	N.OP
		[°C]	[°C]	[°C]		[°C]	[°C]		[°C]	[°C]	[°C]	[°C]
101	Battery	10	9.2	**19.2**		8.9	**18.9**		-20	50	-30	60
102	SRSE	10	1.7	**11.7**		1.3	**11.3**		-20	50	-30	60
103	PGBE	10	10.6	**20.6**		10.5	**20.5**		-20	50	-30	60
104	CDMU	10	11.6	**21.6**		11.5	**21.5**		-20	50	-30	60
105	TRSP2	10	2.3	**12.3**		2.2	**12.2**		-20	50	-30	60
106	RFDN	10	0.0	**10.0**		-0.3	**9.8**		-20	50	-30	60
107	TRSP1	10	1.5	**11.5**		1.3	**11.3**		-20	50	-30	60
108	PCU	10	12.8	**22.8**		12.7	**22.7**		-20	50	-30	60
4090	ECE inside PGB	10	30.6	**40.6**		7.2	**17.2**					
72000	Tank1	10	0.4	**10.4**		0.2	**10.2**					
72100	Tank2	10	-0.5	**9.5**		-0.7	**9.4**					
70000	Antenna +Z	10	20.6	**30.6**		19.0	**29.0**					
70100	Antenna +Z	10	46.7	**56.7**		46.9	**56.9**					
71000	Antenna -Z	10	-33.3	**-23.3**		-28.0	**-18.0**					
71100	Antenna -Z	10	-46.4	**-36.4**		-45.7	**-35.7**					
73110	ESS sensor	10	16.5	**26.5**		16.5	**26.5**					
73120	ESS sensor	10	16.5	**26.5**		16.5	**26.5**					
73210	CSS sensor	10	17.9	**27.9**		18.1	**28.1**					
73310	SRS sensor	10	15.3	**25.3**		15.3	**25.3**					
74000	EPSA 1	10	25.1	**35.1**		25.0	**35.0**					
75000	EPSA 2	10	25.0	**35.0**		25.0	**35.0**					
Tavg	M1 Mass	10	14.4	**24.4**		-0.2	**9.8**					
Tavg	M2 Mass	10	13.5	**23.5**		-0.1	**9.9**					
Tavg	Capacitive Plate1	10	14.3	**24.3**		-0.1	**9.9**					
Tavg	Capacitive Plate2	10	14.3	**24.3**		-0.1	**9.9**					
Tavg	Capacitive Plate3	10	14.3	**24.3**		-0.1	**9.9**					
Tavg	Capacitive Plate4	10	14.3	**24.3**		-0.1	**9.9**					
Tavg	Upper Shaft	10	26.7	**36.7**		3.8	**13.8**					
Tavg	Lower Shaft	10	4.2	**14.2**		-3.8	**6.2**					

Figure 4.2-13: CASE5 – Hot case SAA=28.5° PGB aluminized – Units temperature



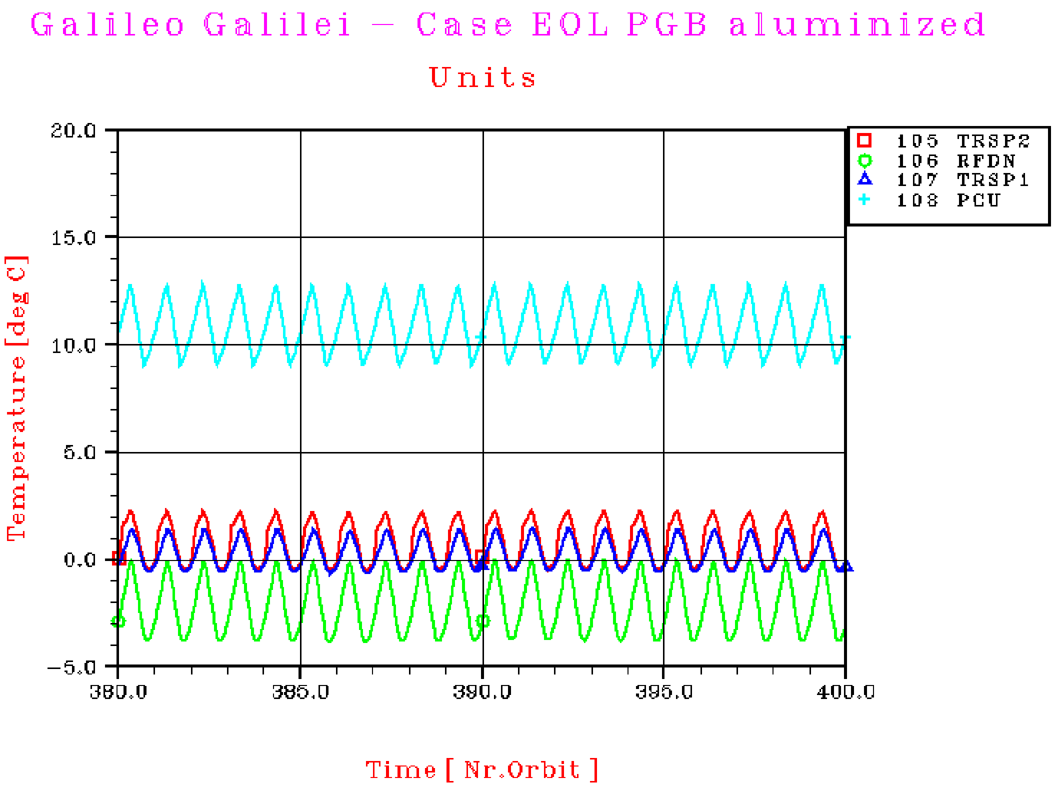
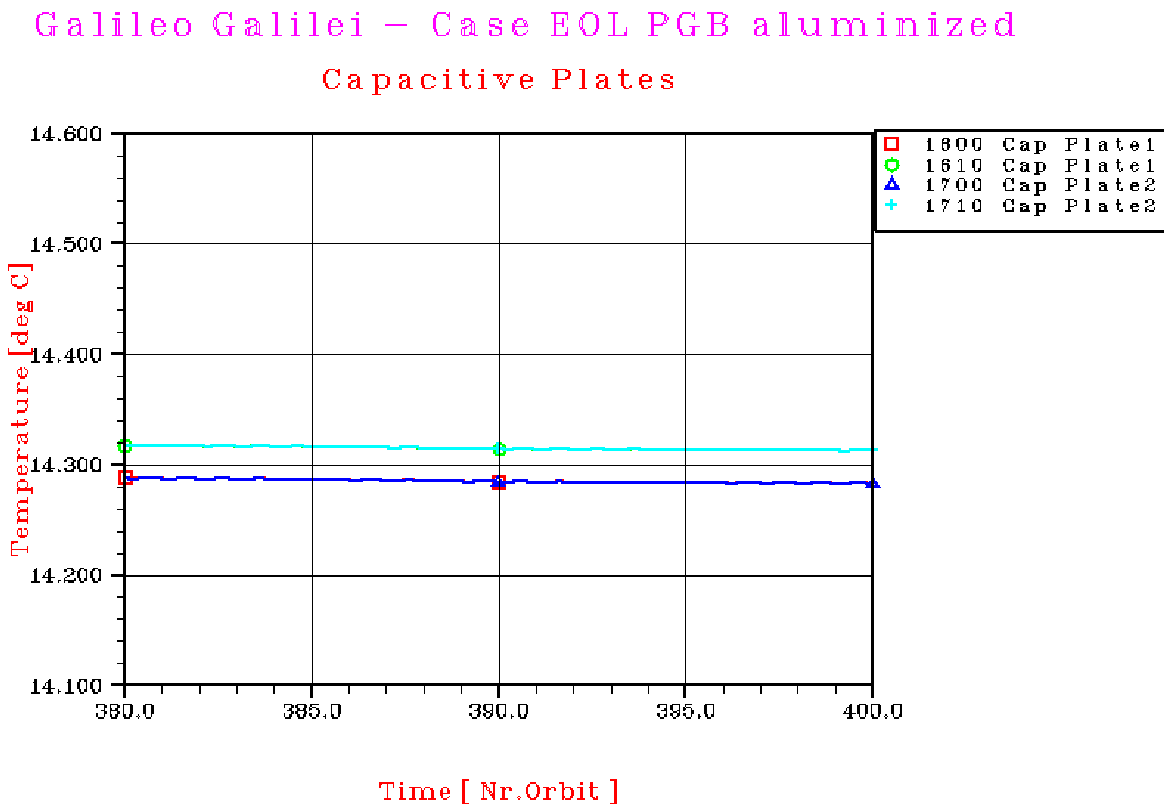


Figure 4.2-14: CASE5 – Hot case SAA=28.5° PGB aluminized – Capacitive Plates



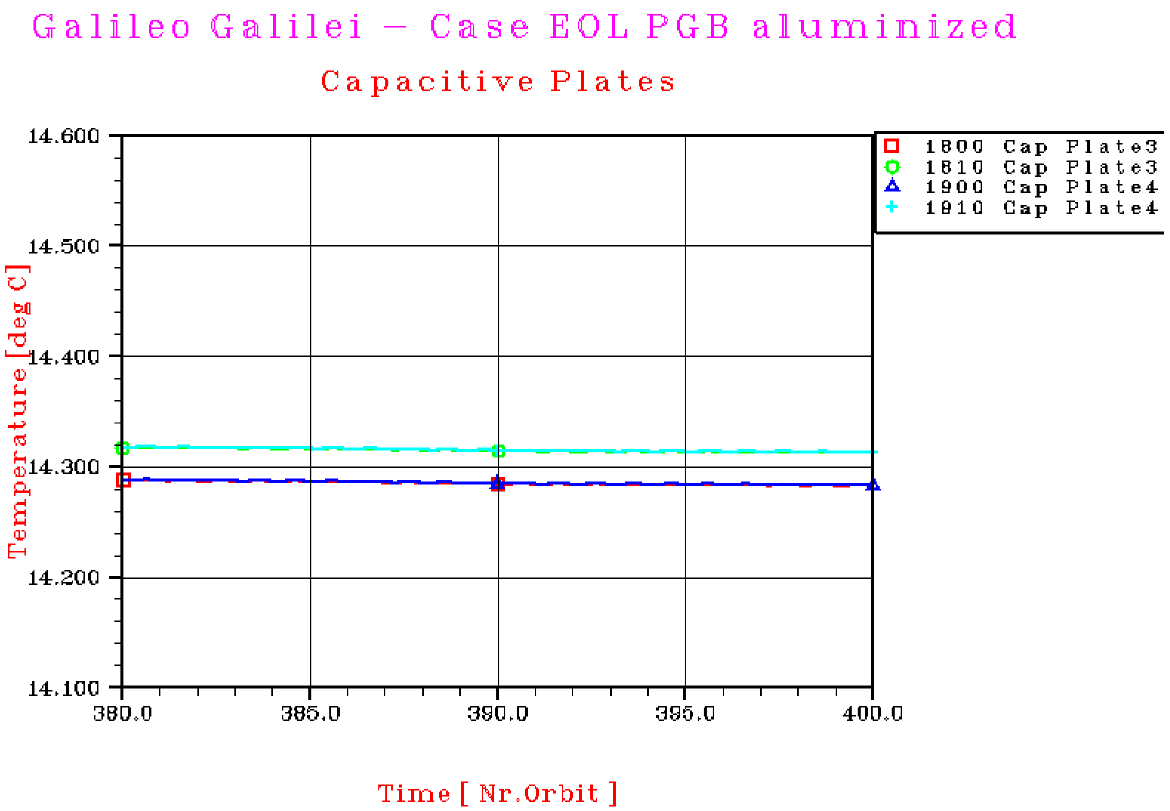
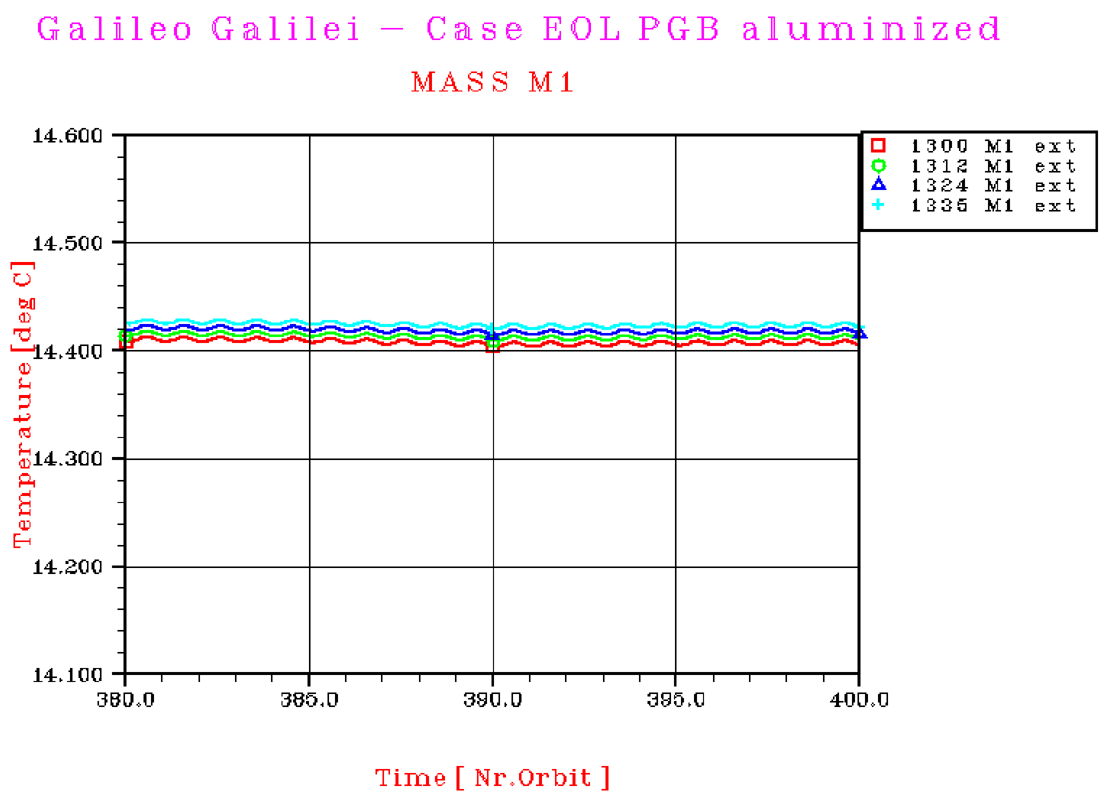


Figure 4.2-15: CASE5 – Hot case SAA=28.5° PGB aluminized – Mass temperature



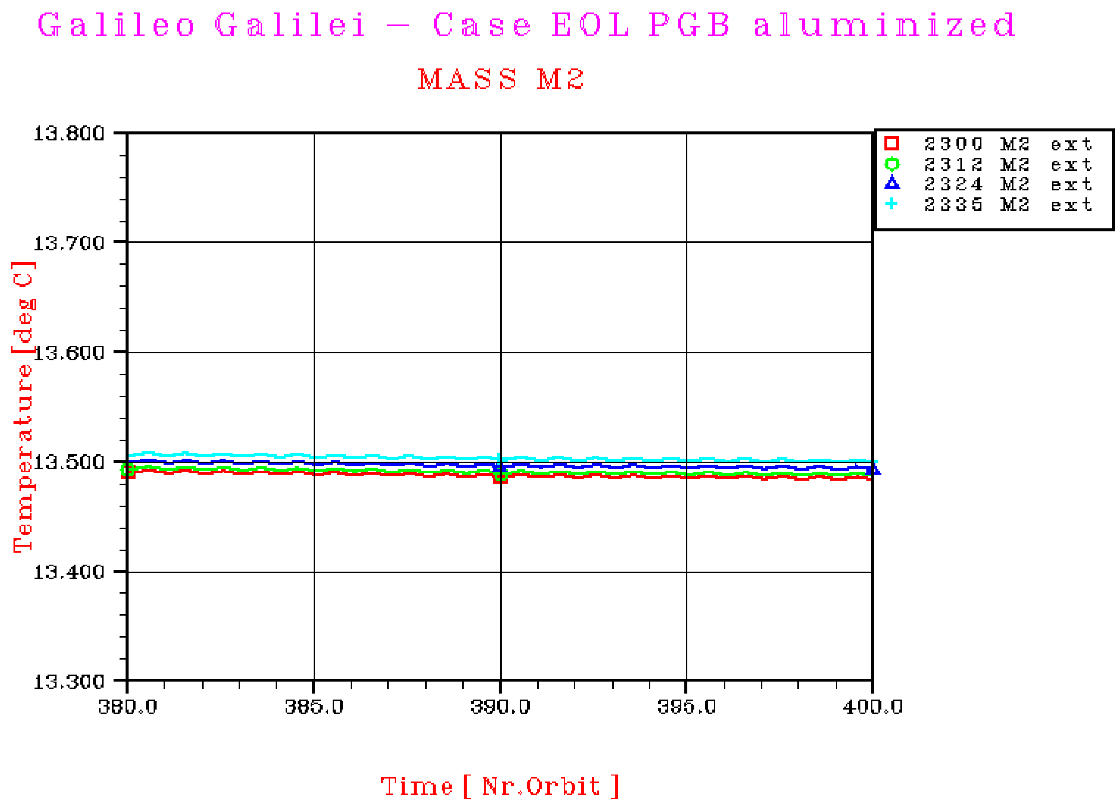
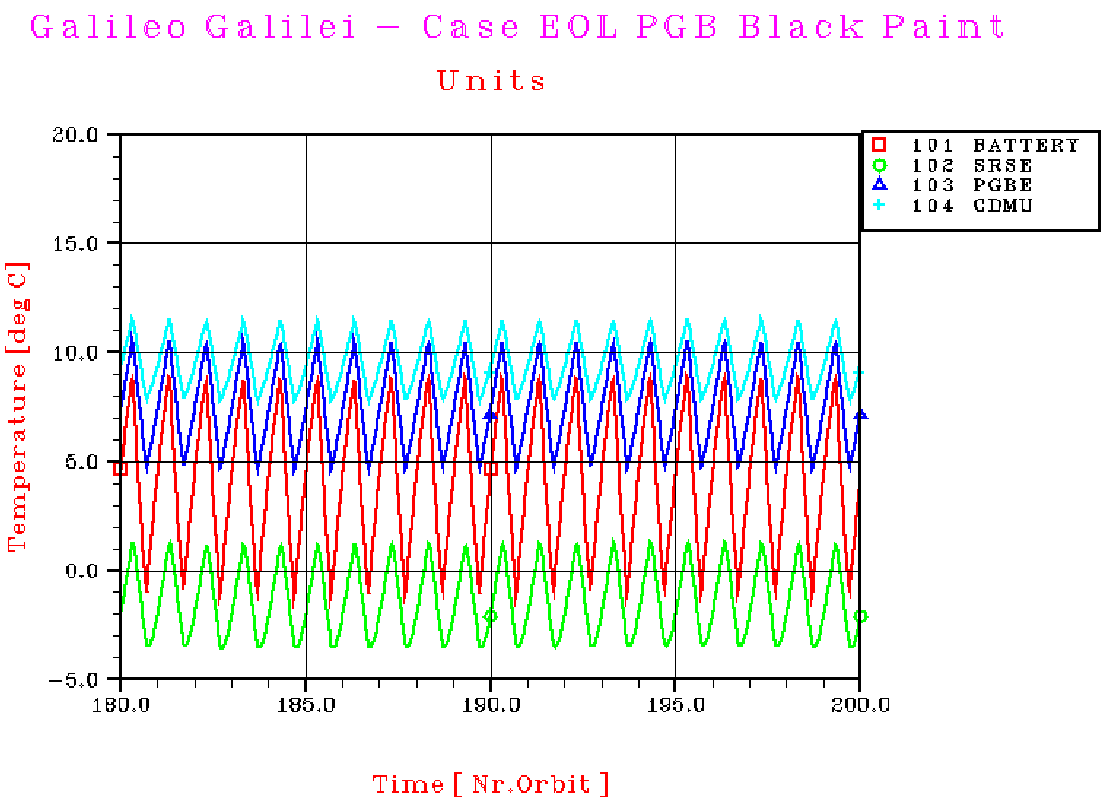


Figure 4.2-16: CASE6 – Hot case SAA=28.5° PGB black paint – Units temperature



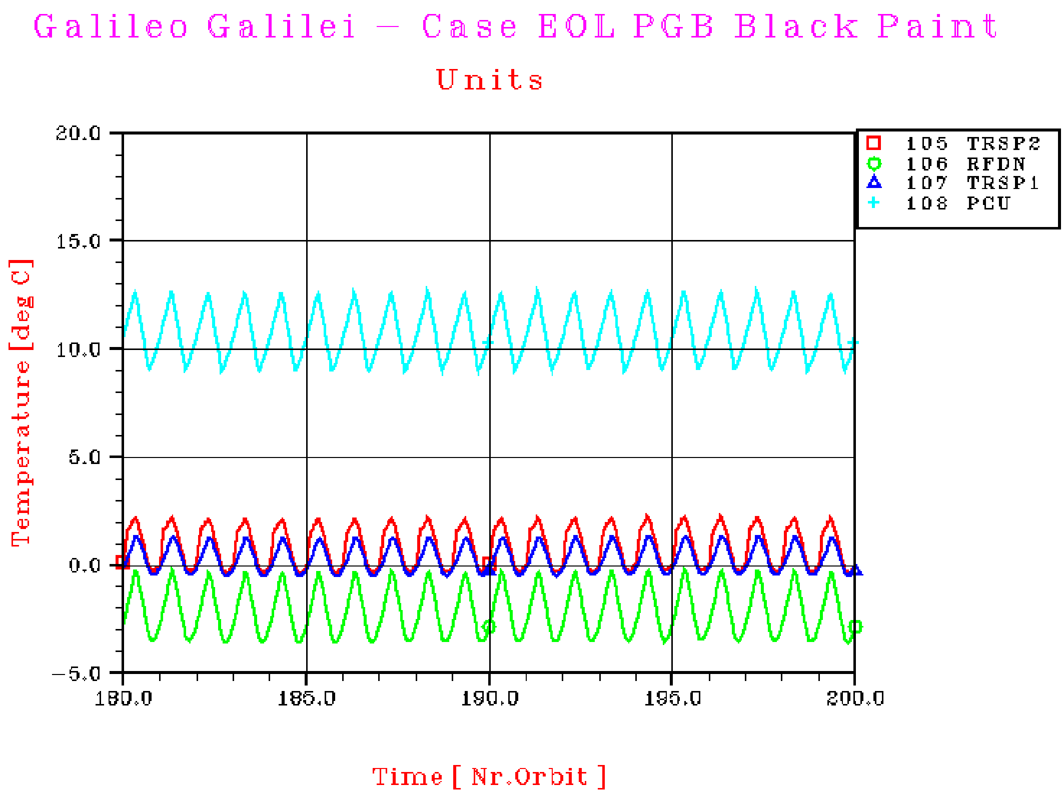
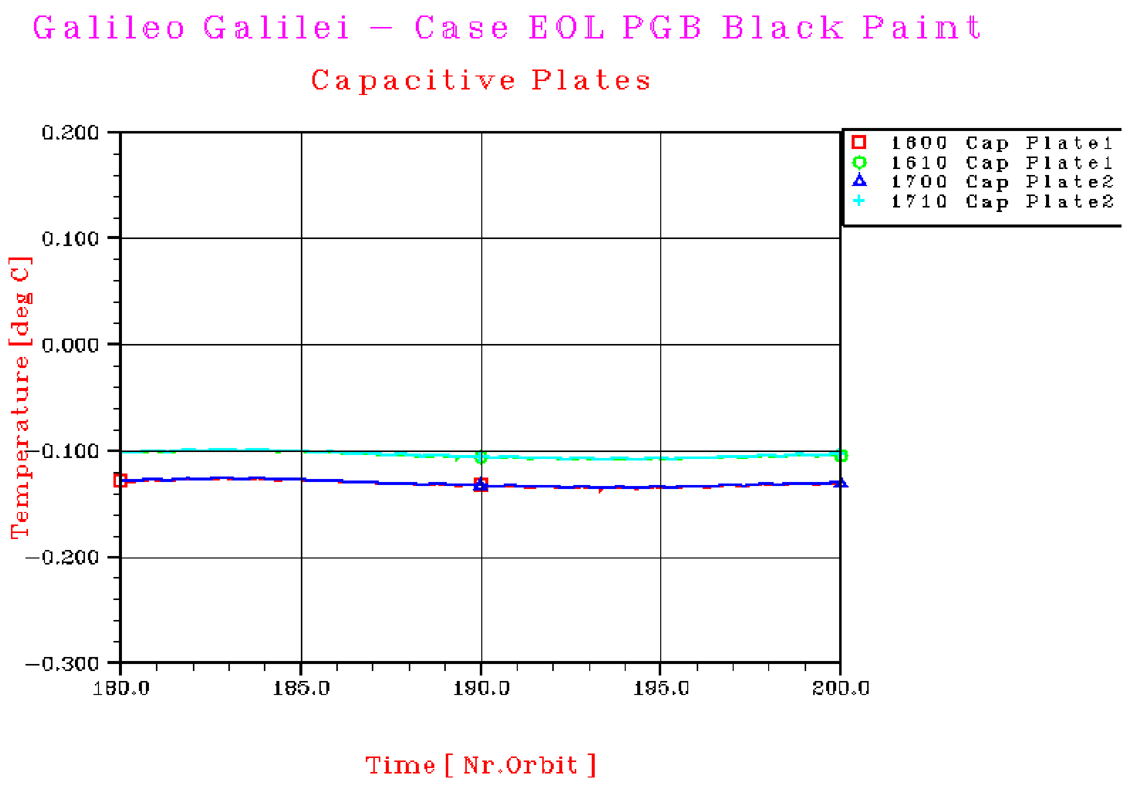


Figure 4.2-17: CASE6 – Hot case SAA=28.5° PGB black paint – Capacitive Plates



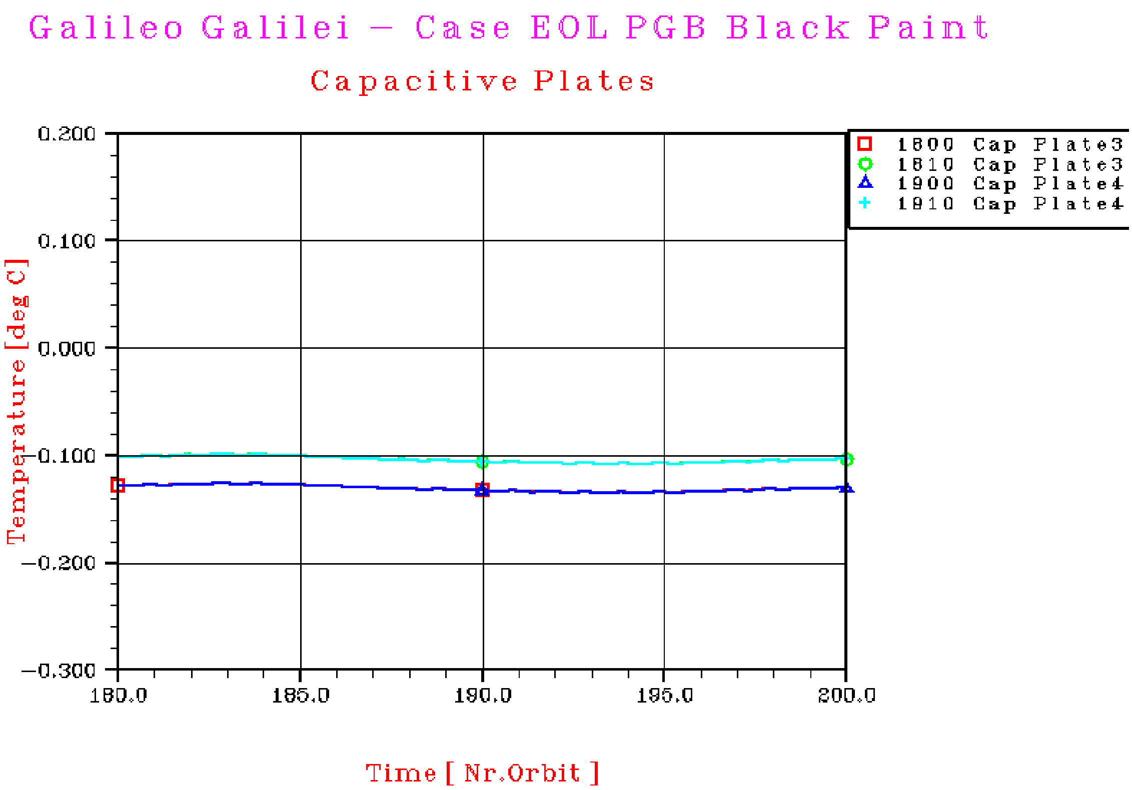
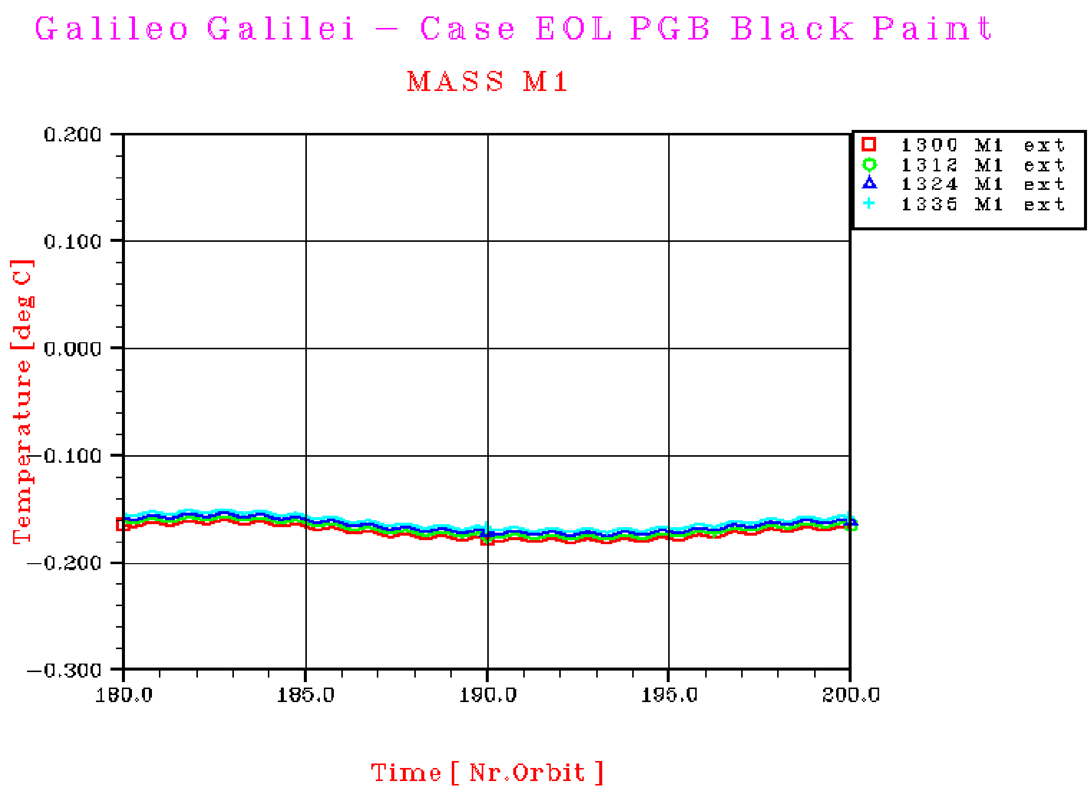
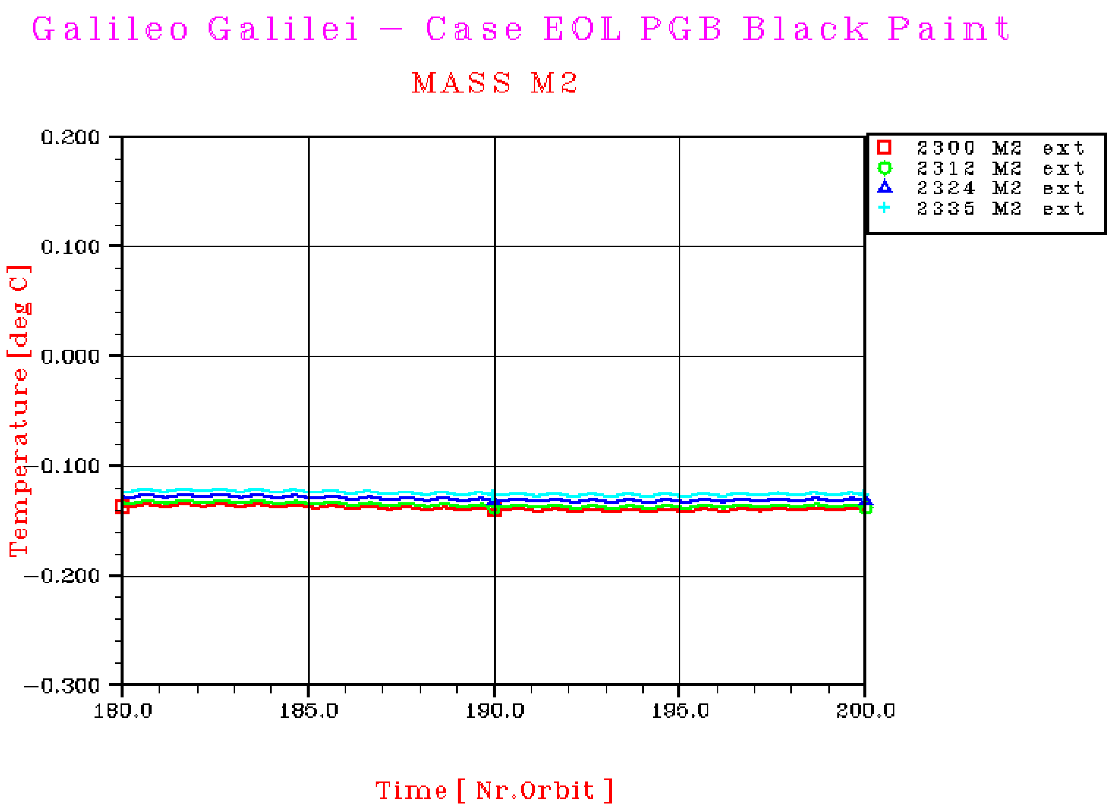


Figure 4.2-18: CASE6 – Hot case SAA=28.5° PGB black paint – Mass temperature





4.3 GG- Temperature stability requirement verification

For every case analysed the temperature requirements as reported in paragraph 3.3 are computed and verified; results are here reported:

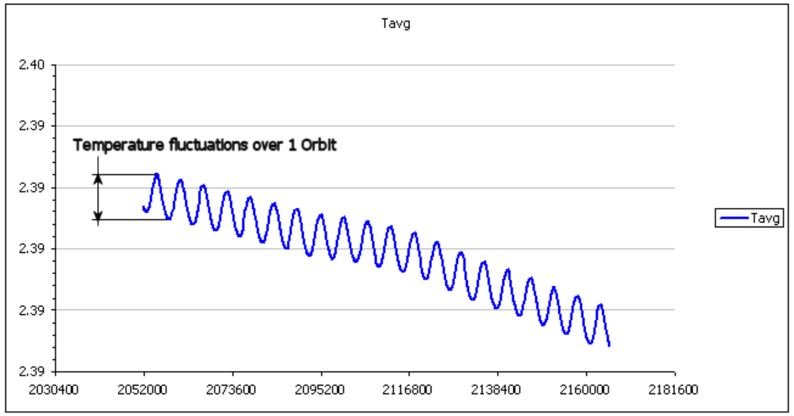
Test Mass mean temperature stability better than 0.1°C/day

The average temperatures of both test masses have been computed and the maximum Delta temperature variation over a period of 1 day has been considered in order to verify the stability requirement. Results for Mass M1 & M2 in all cases analyzed are here reported:

	CASE1		CASE2		CASE3		CASE4		CASE5	SAA 28.5°	CASE6	SAA 28.5°
	Cold Case	PGB ε≤0.05	Hot Case	PGB ε≤0.05	Cold Case	PGB ε=0.88	Hot Case	PGB ε=0.88	Hot Case	PGB ε≤0.05	Hot Case	PGB ε=0.88
	T average	*Max ΔT/day*	T average	Max ΔT/day	*T average*	*Max ΔT/day*	*T average*	*Max ΔT/day*	*T average*	*Max ΔT/day*	*T average*	*Max ΔT/day*
Mass M1		**0.0042**		**0.0203**		**0.0028**		**0.0064**		**0.0055**		**0.0148**
Min Avg Temp	2.386		**14.042**		-15.491		-1.664		14.417		-0.178	
Max Avg Temp	2.391		**14.064**		-15.485		-1.651		14.425		-0.159	
Mass M2		**0.0113**		**0.0237**		**0.0007**		**0.0026**		**0.0065**		**0.0025**
Min Avg Temp	1.393		**13.173**		-15.490		-1.664		13.497		-0.133	
Max Avg Temp	1.408		**13.202**		-15.488		-1.660		13.506		-0.128	

<u>Temperature fluctuations in the proof masses shall not exceed 0.2°C in 1 day.</u>

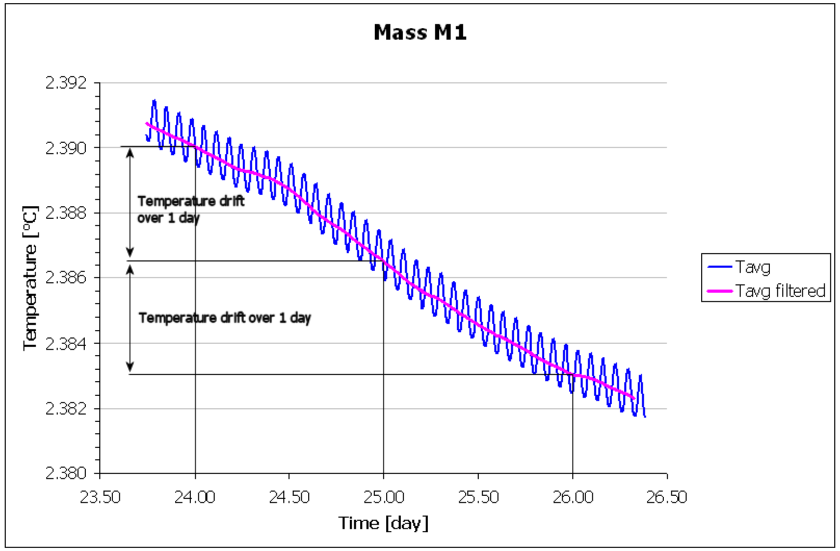
The temperature fluctuation has been computed as the maximum temperature oscillation on Test Masses considered over a period of 1 orbit. The temperature plot gives an example of the temperature oscillation considered in the evaluation of the requirement:



	CASE1	CASE2	CASE3	CASE4	CASE5 – SAA 28.5°	CASE6 – SAA 28.5°
	Cold Case - PGB ε≤0.05	Hot Case - PGB ε≤0.05	Cold Case - PGB ε=0.88	Hot Case - PGB ε=0.88	Hot Case - PGB ε≤0.05	Hot Case - PGB ε=0.88
	Max Fluctuation temper.	*Max Fluctuation temper.*	*Max Fluctuation temper.*	*Max Fluctuation temper.*	*Max Fluctuation temper.*	*Max Fluctuation temper.*
Mass M1	**0.00136**	**0.00296**	**0.00143**	**0.00247**	**0.00422**	**0.00484**
Mass M2	**0.00093**	**0.00183**	**0.00065**	**0.00114**	**0.00216**	**0.00231**

Linear temperature drift in the proof masses shall not exceed 0.2°C/day.

In order to evaluate the requirement on the Masses drift temperature, the average temperatures obtained by analysis have been filtered to reduce the temperature oscillation induced by the variation of orbit environment, mainly due to the eclipse effect.
In particular the technique known as Moving Average Filter has been applied on each Mass average temperature results; the obtained filtered average temperature has been used to compute the drift requirement over a period of 1 day, and the maximum values obtained for each cases are reported in the following table.
The following temperature plot gives an example of the filtered temperature considered in the evaluation of the drift requirement.



	CASE1	CASE2	CASE3	CASE4	CASE5 – SAA 28.5°	CASE6 – SAA 28.5°
	Cold Case - PGB ε≤0.05	Hot Case - PGB ε≤0.05	Cold Case - PGB ε=0.88	Hot Case - PGB ε=0.88	Hot Case - PGB ε≤0.05	Hot Case - PGB ε=0.88
	Max Drift temper.	*Max Drift temper.*	*Max Drift temper.*	*Max Drift temper.*	*Max Drift temper.*	*Max Drift temper.*
Mass M1	0.00354	0.01915	0.00241	0.00564	0.00342	0.01305
Mass M2	0.01101	0.02309	0.00045	0.00210	0.00554	0.00168

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Axial temperature gradient at the level of the Shaft cylinder shall not exceed 1 °C/Shaft length

This requirement has been verified on the gradient measured along the Upper and Lower Shaft.
Two numerical values are provided, one measured as the gradient along entire Shaft length (delta temperature between Shaft edges shall be < 1°C) and the second value as a gradient / unit length (requirement shall be < 4°/m)

	CASE1 – SAA 0°	CASE2 – SAA 0°	CASE3 – SAA 0°	CASE4 – SAA 0°	CASE5 – SAA 28.5°	CASE6 – SAA 28.5°
	Cold Case - PGB ε≤0.05	Hot Case - PGB ε≤0.05	Cold Case - PGB ε=0.88	Hot Case - PGB ε=0.88	Hot Case - PGB ε≤0.05	Hot Case - PGB ε=0.88
	Axial Gradient	*Axial Gradient*	*Axial Gradient*	*Axial Gradient*	*Axial Gradient*	*Axial Gradient*
Upper Shaft						
/shaft length	**0.82**	**0.76**	**0.24**	**0.24**	**0.94**	**0.67**
/m	3.28	3.04	0.96	0.96	3.76	2.68
Lower Shaft						
/shaft length	**0.57**	**0.53**	**0.19**	**0.19**	**0.68**	**0.55**
/m	2.28	2.12	0.76	0.76	2.72	2.2

In all the analyzed cases the location of the dissipating unit inside the PGB (ECE at 4 W) has been considered close to the Upper Shaft; this assumption lead to have the higher gradient computed on the Upper shaft respect to the Lower Shaft.

As expected the thermal cases with PGB internal finish at high emissivity show a lower gradient on the Shaft respect to the low emissivity cases; nevertheless in all cases the gradient is maintained within the requirement, with a worst axial gradient computed of 0.94°/shaft length versus the requirement of 1°/shaft length; this case take into account the Sun Fluxes impingement on the top side of the satellite, internal PGB with low emissivity finish and ECE location close to Upper Shaft.

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4.4 GG – Heater power dissipation

Heater power control will be commanded through dedicated heater circuits generally controlled on a "ON-OFF logic" between temperature thresholds based on automatic control via CDMU at the minimum "operating/non operating" temperature thresholds.

The following table provides the averaged heater power need in the analysed Cold Cases and considering a 10 °C of margin above the minimum operative design limit of the units. With actual temperature design operative ranges assumed between -20°/+50°C for all internal units, the heater thresholds have been considered with an On-Off settings between -10°C / -9°C.
The Heater Power dissipations obtained are reported in the following table:

Node	Description	CASE 1 Cold Case PGB $\varepsilon \leq 0.05$	CASE 4 Cold Case PGB $\varepsilon = 0.88$
		Heater Power [W]	Heater Power [W]
101	Battery	**1.51**	**1.81**
102	SRSE	**3.17**	**3.54**
103	PGBE	**0.00**	**0.00**
104	CDMU	**0.00**	**0.00**
105	TRSP2	**3.59**	**4.29**
106	RFDN	**1.65**	**1.77**
107	TRSP1	**3.81**	**4.47**
108	PCU	**0.00**	**0.00**
	Total Heater Power need	**13.73**	**15.88**

Remark: Hot cases do not foresee any heater power consumption, so they are not included in the table.

5. CONCLUSIONS

According to the thermal analysis results, a passive thermal control is sufficient to maintain the satellite and equipment within temperature ranges applicable to the operative status for all mission phase; moreover also the stability criteria (Mass fluctuations, drift and mean temperature requirements), and gradient temperature on Shaft arms are well satisfied within the limits required.

A certain number of assumptions have been introduced in the Thermal mathematical model and they need to be reviewed and harmonized with the final payload design. Main assumptions introduced are here summarized:

- Test Mass 1 has been considered in Tungsten;
- Test Mass 2 has been considered in Polyethylene, contained inside an aluminum body;
- Test Mass1, Test Mass2 and Capacitive Plates have been considered with a Gold finish covering (ε=0.04) in all cases analysed;
- Conservative power dissipation profiles have been considered: maximum dissipation power is considered while the S/C is in sunlight, while minimum dissipation power is considered while the S/C is in eclipse, leading to a wide variation in the internal produced heat for each orbit (225W in sunlight and 44.4W in eclipse);
- ECE location inside the PGB has been considered close to the Upper Shaft;
- The PGB support structure is made of aluminum, conductively connected to the satellite structure by two laminar CuBe alloy springs sets only (GL = 0.0021 W/K each);
- PGB external covering has been considered as a 20 layer MLI with aluminized Kapton;
- External radiative areas have been covered with a Silver Teflon Tape;

The temperature of all internal equipments are maintained within assumed operative temperature ranges (-20°/+50°C) in all cases analyzed with relevant margins to high limits temperature; the actual temperature level could allow to reduce the size of the radiators on the cylindrical structure still maintaining the internal equipment within their temperature limits.

At the current level of analysis the heater need is foreseen only in Cold conditions (BOL property and minimum Solar Constant level) with a requested heater load of 16 W.

The stability criteria are well satisfied within the requested limits; the higher values computed by analysis are here reported:

Criteria	Requirement	Stability results	Note
Test Mass mean temperature	0.1° / day	0.0237°/day	M2 Mass /Hot case /PGB low emissivity/ SAA=0°
Test Mass temperature fluctuations	0.2° / day	0.00484°/orbit	M1 Mass /Hot Case /PGB high emissivity/ SAA=0°
Test Mass temperature drift	0.2° / day	0.02309°/day	M2 Mass /Hot case /PGB low emissivity/ SAA=0°
Shaft Axial temperature gradient	1° / shaft length	0.94°/ shaft length	M1 Mass /Hot case /PGB low emissivity/ SAA=28.5°

Use of black paint inside the PGB (masses and plate excluded) makes the payload elements more sensitive to the external disturbances; on the other hand, black paint allows the internal components of the payload to approach the equilibrium conditions faster.

Power dissipation inside the PGB on ECE, should be minimized, as it affects the performance in terms of gradient inside PGB; with the actual thermal design the axial temperature gradients on shaft arms is still maintained below the requirement, but an eventual increase of power dissipation on the ECE will lead to exceed the requirement itself.

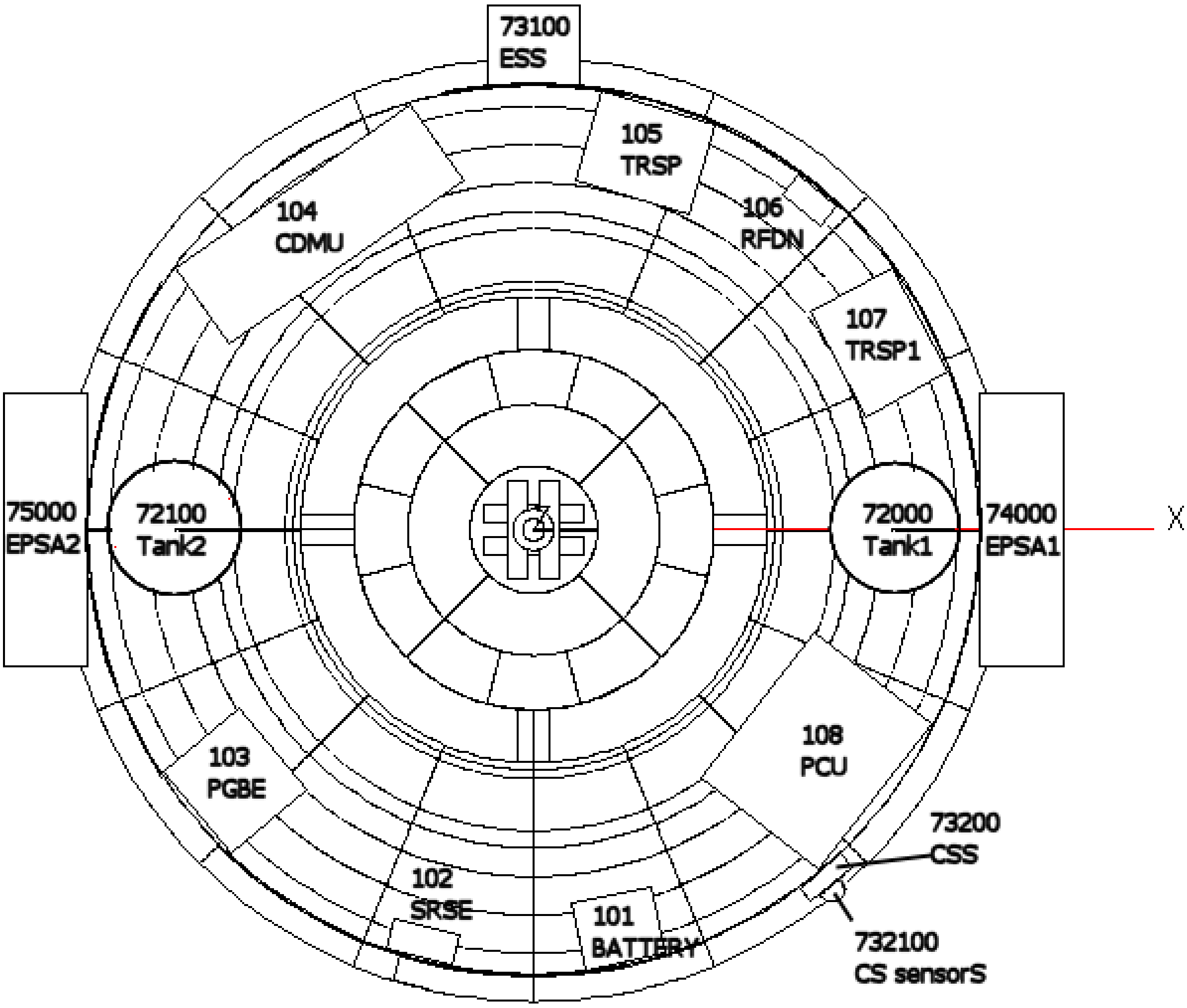
Due to the high decoupling of the internal payload from the rest of the S/C, long times are needed to approach the equilibrium temperatures, even if the temperature variations during this time are within the requirements. A more detailed analysis will be necessary to assess the time constant of the system.

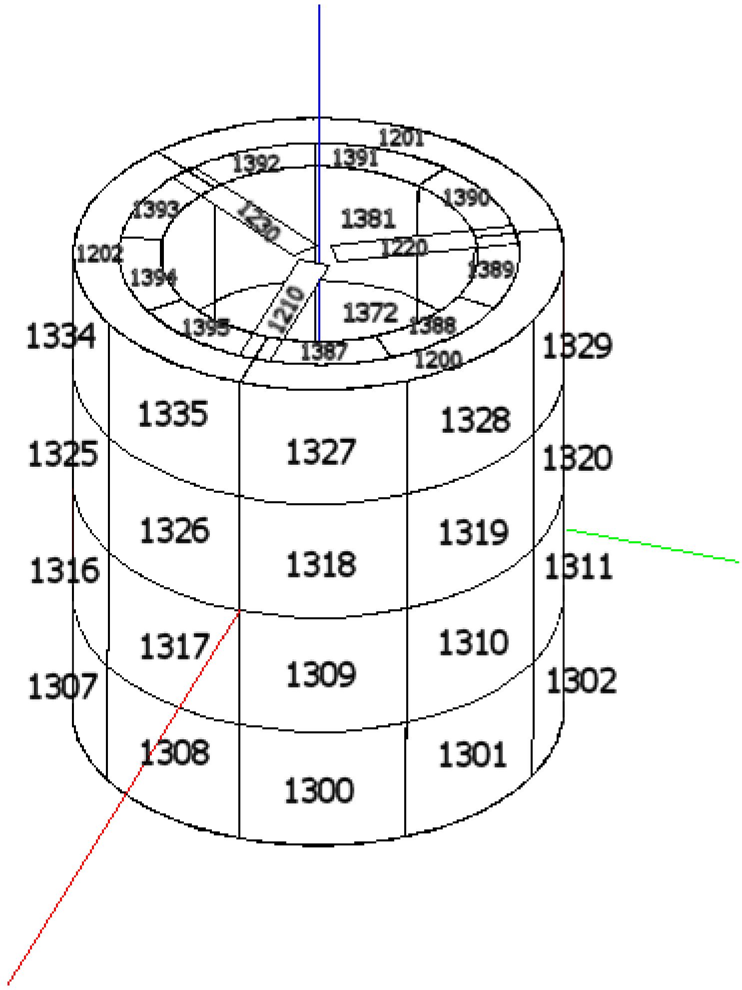
MLI, structural elements and solar panel temperatures show normal temperature levels and are of no concern.

6. ANNEX

6.1 Annex1 – GMM Nodal Breakdown

In the following figures, the nodal breakdown of the satellite is presented.

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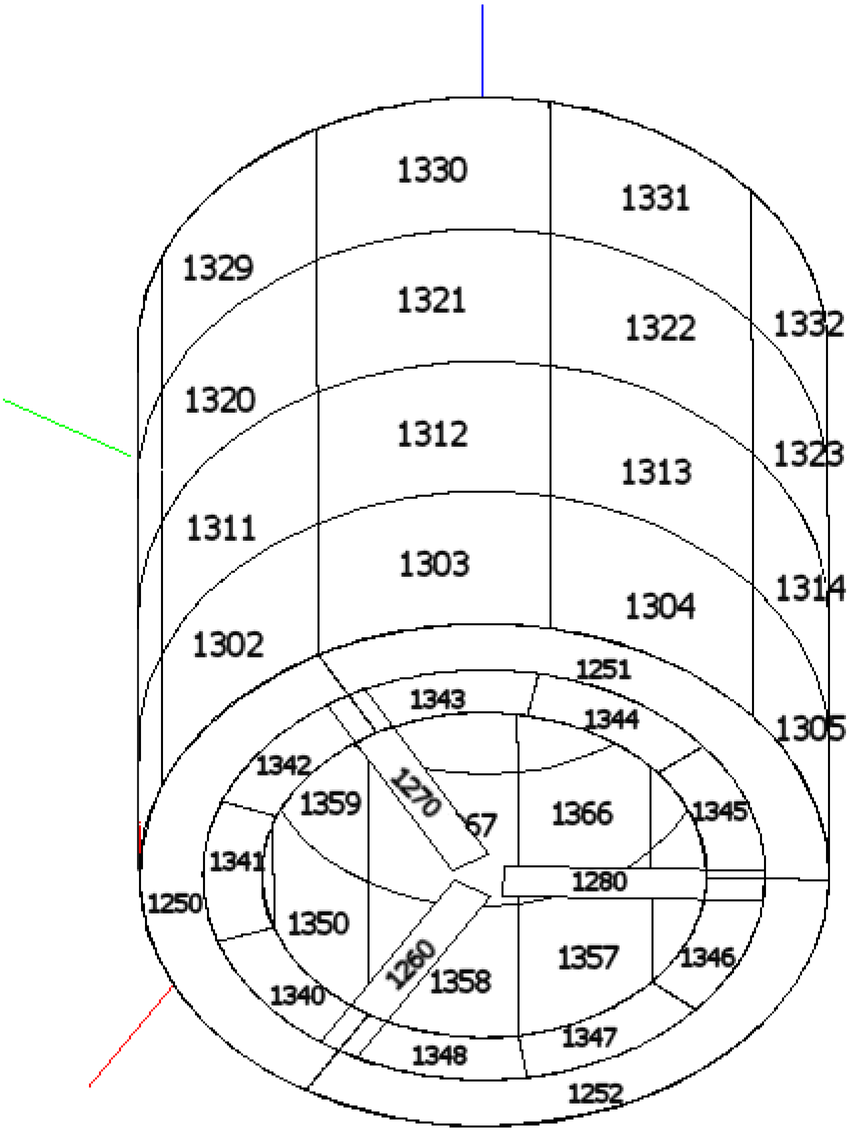

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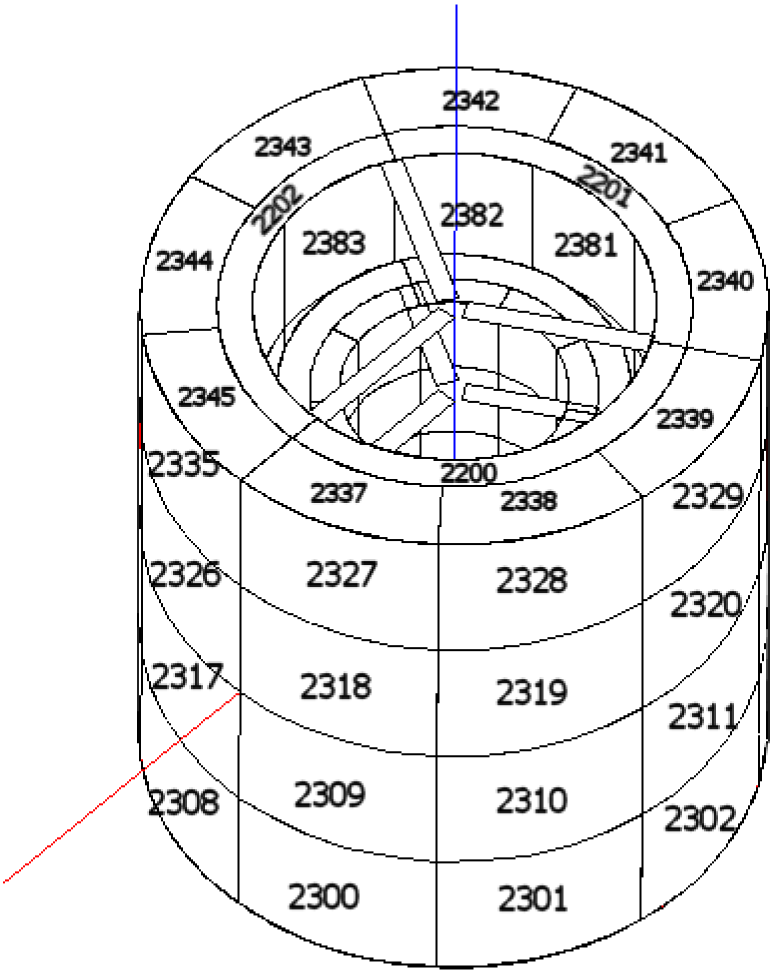
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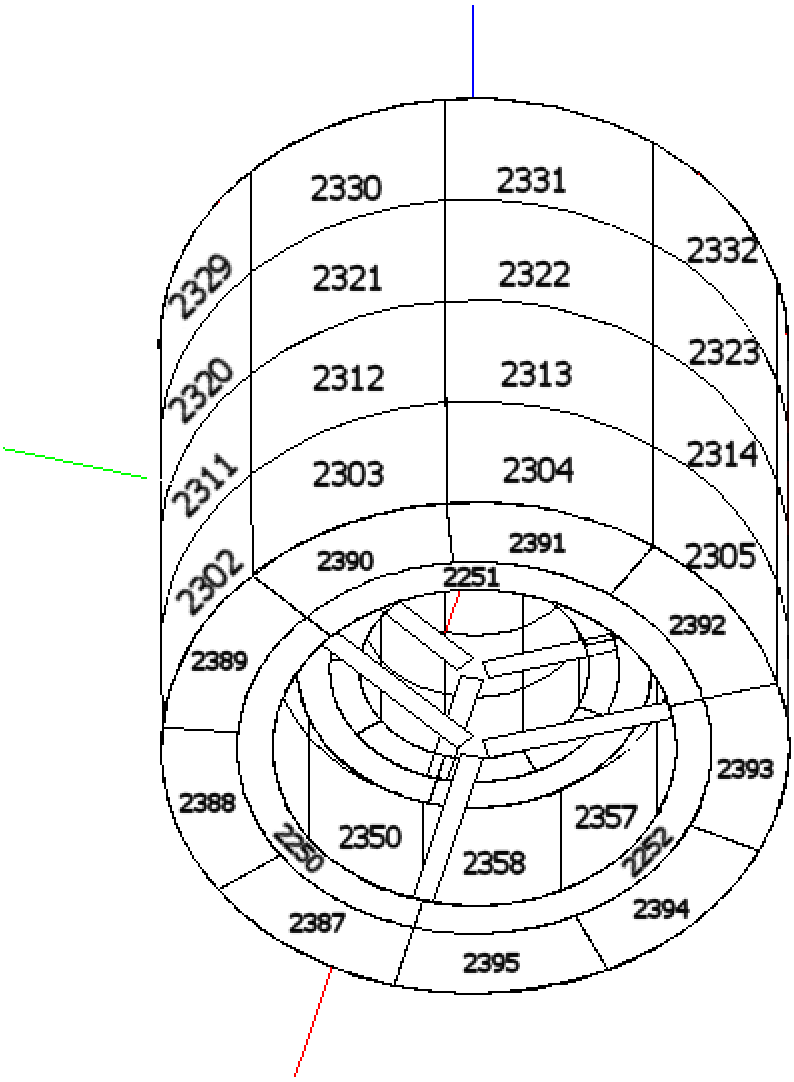
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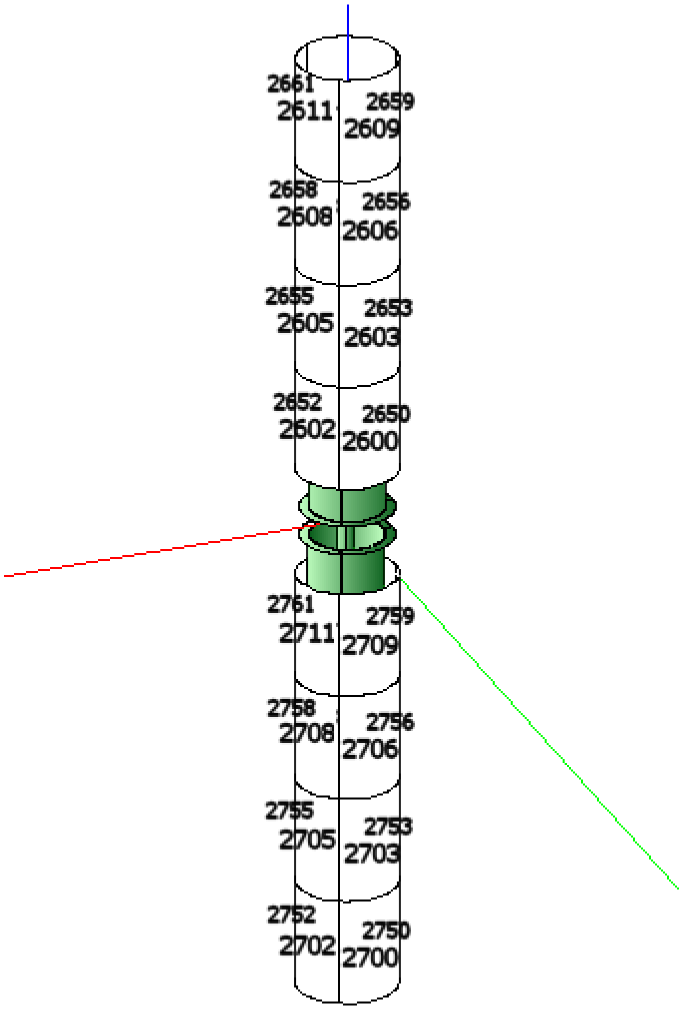
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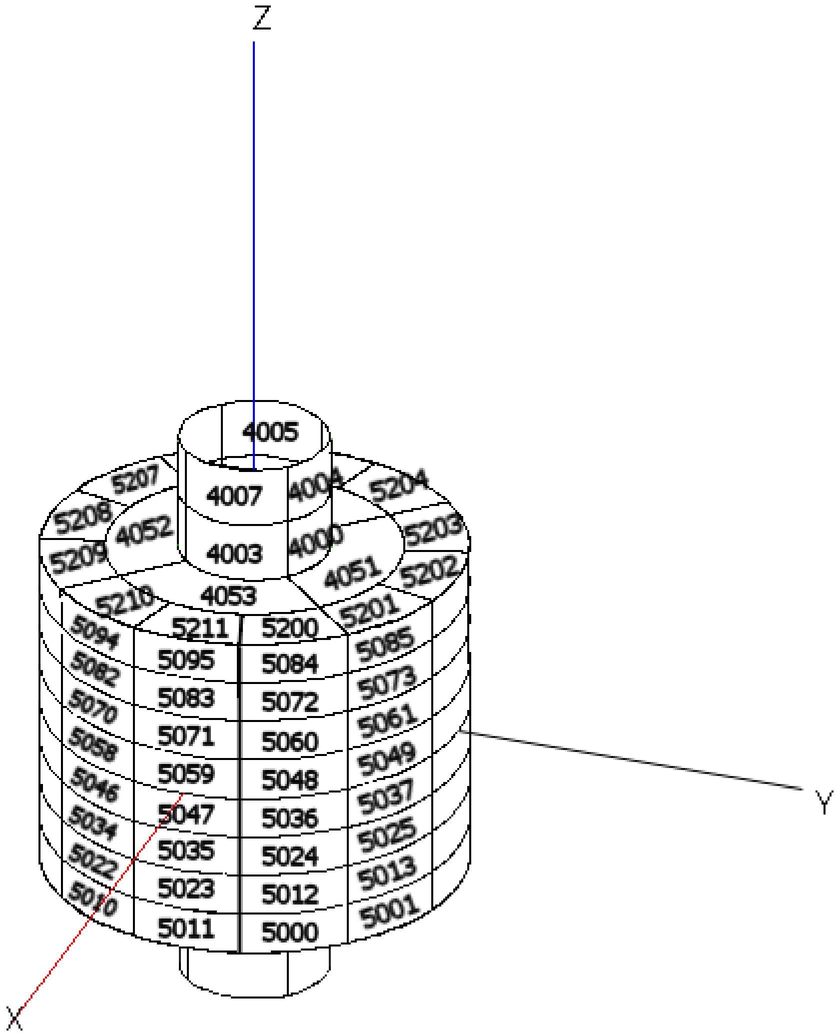
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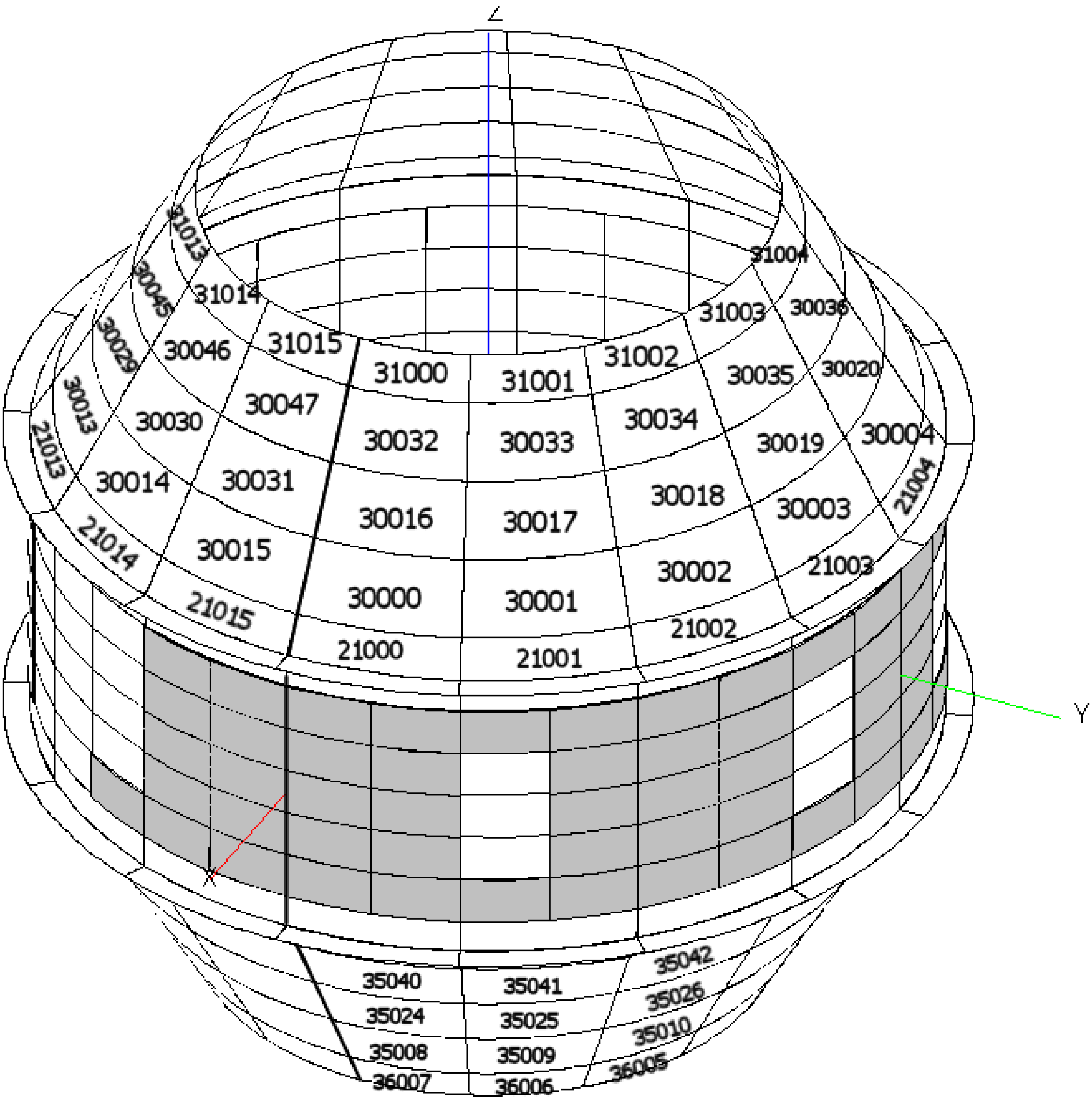
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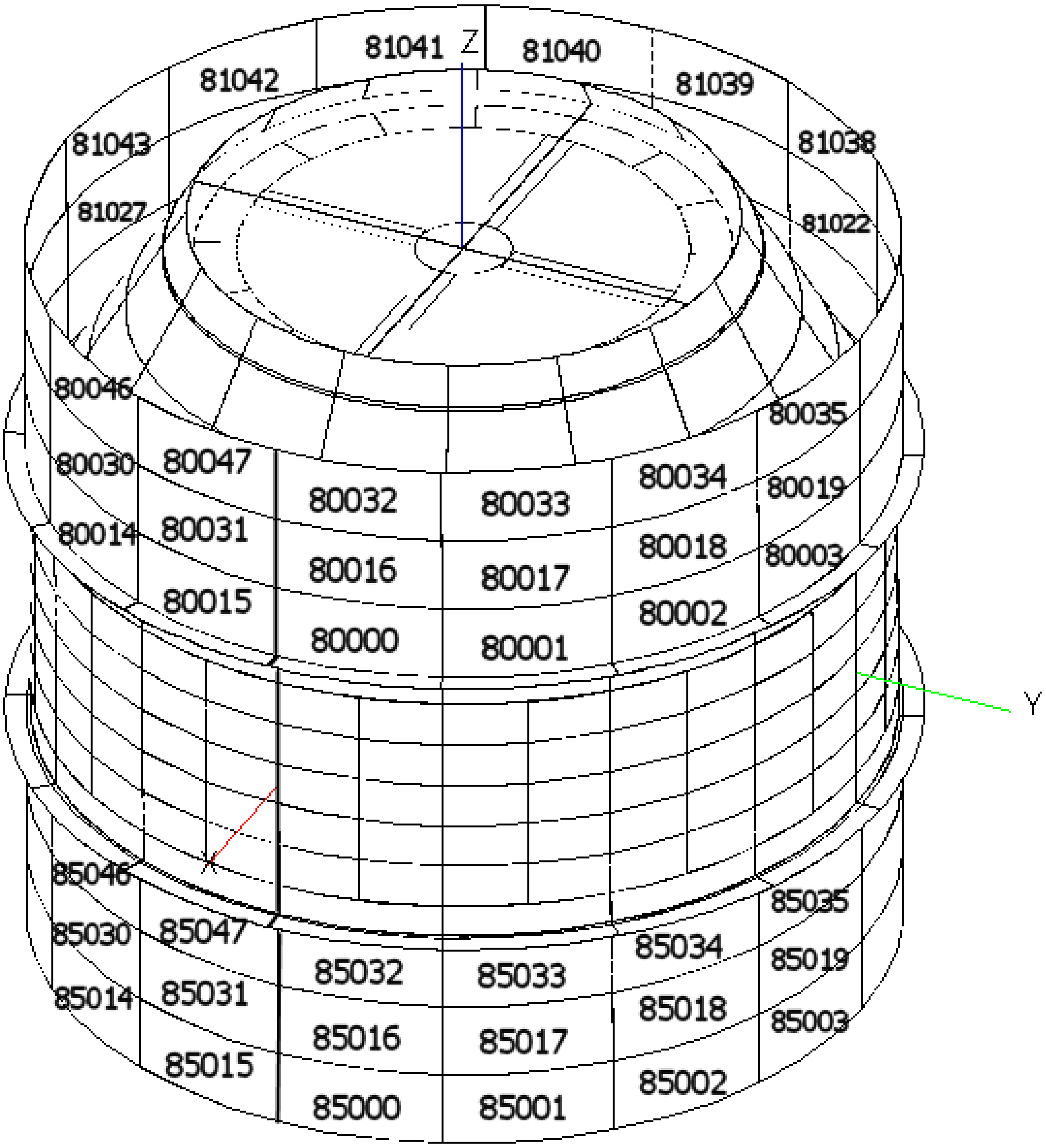
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